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The PACCAR Pavement Test Section—

Instrumentation and Validation

by

Brian Christopher Winters

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

University of Washington

1993

Approved by ______________________________
Joe P. Mahoney (Chairperson of Supervisory Committee)

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Abstract

The PACCAR Pavement Test Section—
Instrumentation and Validation

by Brian Christopher Winters

Chairperson of the Supervisory Committee: Professor Joe P. Mahoney
Department of Civil Engineering

This study discusses the instrumentation and validation of a full-scale, instrumented, flexible pavement section at the PACCAR Technical Center designed to measure critical pavement responses evaluated in the mechanistic-empirical analysis methodology. Falling Weight Deflectometer (FWD) testing was conducted to characterize the layer properties of the pavement section and compare the strains measured under the FWD load to those calculated using layered elastic analysis.

From backcalculated layer moduli for the PACCAR section, it was found that the saturated condition of the subgrade triggered the stiff layer algorithm in EVERCALC 3.3. Further, a stiff layer modulus of 40 or 50 ksi (instead of the traditional value of 1000 ksi) resulted in more realistic layer moduli for the other pavement layers. This has been true for a series of FWD tests during three seasons (Fall, Summer, and Winter).

Analysis of the strains under FWD loading conducted on October 10, 1991 has shown that 90 percent of the measured strains are within ± 20 percent of their calculated values. Fifty percent of the strains measured during the FWD testing conducted on February 3, 1993 were within ± 20 percent of calculated. The gauges measuring horizontal tensile strain at the bottom of the AC have shown the best agreement with theoretical strains calculated using CHEVPC. Strains measured during FWD and truck testing on June 15, 1992 and May 1, 1992, respectively, resulted in marginal agreement between measured and calculated strains. While the reasons for this poor agreement are unknown, it is speculated that the uncertainty of wheel alignment over the cores (gauges) is a major factor in the May truck testing.

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Work on this study has truly been a team effort and as such, I owe a debt of gratitude to every member of the team for their contribution. First and foremost, is Professor Joe Mahoney. He has been a truly outstanding mentor and his guidance and support were unending. Derald Christensen gave freely of his time and wealth of experience. The engineers from PACCAR (Dave Menmuir, Tom Moran, Dale Gadbois, and many others) also provided their expert assistance. I thank Professor Steve Kramer and Mr. Newt Jackson for their thorough review of the manuscript. The work of Eva Nachmanson and Duane Wright in producing the final document is also greatly appreciated. Lastly, I thank the United States Army for making all this possible.

DEDICATION

This thesis is dedicated to my wife, Tammie, my sons, Blake and Brent, and my grandparents, Oscar Williams and Alta David. My wife and sons gave of their patience and understanding knowing they would get nothing in return. My grandparents taught me the importance of hard work, doing my best, and an inquisitive mind.

CHAPTER 1

INTRODUCTION

1. THE PROBLEM

The condition of the U.S. highway system has been and continues to be a major concern of both the highway and trucking communities. [1] This is very understandable given the fact that in 1990, combination vehicles with five or more axles accounted for 91 percent of the 18,000 pound equivalent axle loads (ESALs) on rural Interstate highways. [2] This heavy vehicle traffic and the pavement system it travels on combine to generate a perpetual cycle of pavement deterioration and rehabilitation. Increasing truck traffic leads to predictable pavement damage that in turn contributes to potentially increasing dynamic loading of the pavement. This cycle continues until some form of pavement rehabilitation is undertaken. The trucking community alters the design and operation of their vehicles largely due to economic considerations (profit) [1] but also in response to the ride quality (or lack thereof) of the infrastructure to which they are bound. On the other hand, the pavement community is constantly updating design and construction practice to improve pavement performance. Unfortunately, both parties develop a form of "technical tunnel vision" [1] and work to resolve some of the same concerns without the benefit of a possible mutual effort. As such it is recognized that there is a need to improve our mutual understanding of truck pavement interaction. [3] Often, but not always, a beneficial change in one community (such as smoother pavements) benefits the other (less truck/cargo damage). [1]

This lack of collaborative effort can be traced to at least 1965 where representatives of both communities criticized each other for their failure to examine both sides of the issue concerning the use of flotation tires. [4] Representatives of the tire industry criticized the authors from the pavement community for neglecting the aspects of ride quality and vehicle maintenance. The authors admitted to purposefully leaving the vehicular issues to the trucking community.

2. BACKGROUND OF THE RESEARCH STUDY

This thesis is part of a multiphased research project entitled "Truck/Pavement Interaction" being conducted jointly by the University of Washington, University of California-Berkeley, Washington State Department of Transportation (WSDOT), California Department of Transportation (Caltrans), and PACCAR, Inc. This is an attempt to promulgate a mutually beneficial dialog between the pavement and trucking communities. The objective of the research is to investigate how different truck suspensions, tire/axle combinations, tire loads, and tire pressures affect pavement deterioration and conversely how pavement condition affects truck performance and damage. These objectives will be accomplished by operating instrumented trucks over an instrumented pavement section. [1]

3. OBJECTIVES

Before one can begin to study this interaction between pavement and vehicle, a functional, instrumented test section must be established. That is the purpose of this study. A functional test section depends on realistic pavement layer characteristics and responses from the installed instrumentation. Data from a Falling Weight Deflectometer (FWD) will be used to characterize the various layers of the instrumented section using the backcalculation process. The FWD will also be used to evaluate the various responses from the gauges installed in the pavement section.

4. SCOPE OF WORK

This study involves the performance of the instrumented asphalt concrete (AC) pavement section located at the PACCAR Technical Center in Mount Vernon, Washington. It includes an analysis of the material properties of the test section using

EVERCALC 3.3 and a comparison of measured and theoretical strains under known FWD loads using elastic layer analysis.

5. RESEARCH METHODOLOGY

The procedure used to construct and validate the instrumented pavement section included the following steps.

1. Acquiring the various gauges, instrumentation, and other hardware.
2. Pavement coring for gauge installation and determination of layer thicknesses and material characteristics.
3. Installing the wiring and other permanent pieces of the data collection system.
4. Initial testing of gauges and data collection system using a calibration trailer and a FWD.
5. FWD testing over the entire test section.
6. Backcalculating the elastic moduli for each of the pavement layers.
7. Measuring strains during FWD testing.
8. Calculating theoretical strains for FWD testing.
9. Comparing calculated strains to measured strains.

A flow chart of this methodology is presented in Figure 1.

6. REPORT OVERVIEW

This report is divided into six chapters. Chapter 1 contains the general introduction of the study, objectives, scope, and methodology. Chapter 2 is a review of some of the pertinent literature. Some of the general topics discussed in Chapter 2 include: backcalculation of pavement layer moduli, pavement response to load, and results (mostly strain responses) from other instrumented test sections. Chapter 3 provides an evaluation and characterization of the pavement test section. Chapter 4

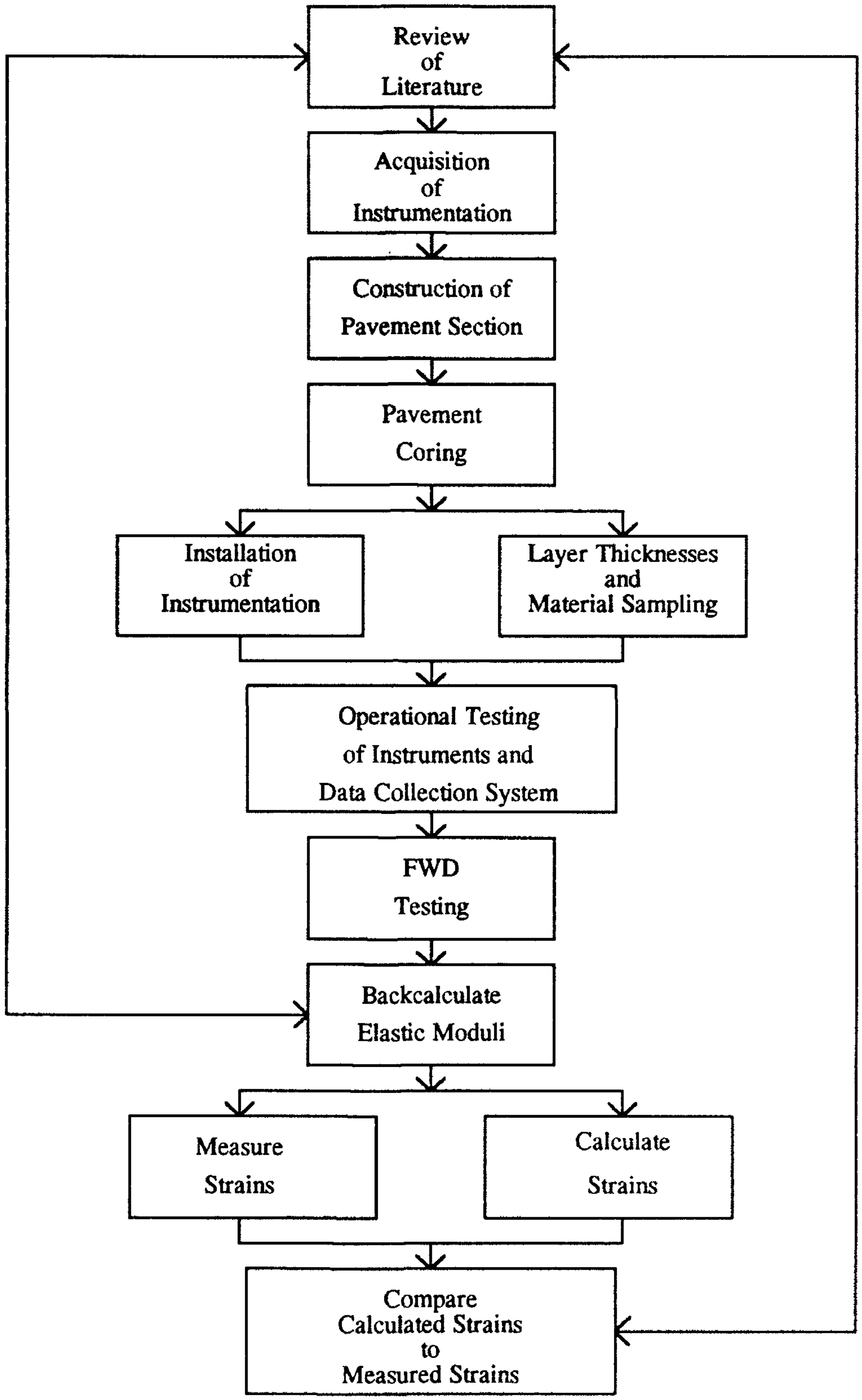


Figure 1. Instrumentation and Initial Evaluation of Test Section

discusses the acquisition and installation of the instrumentation of the test section. Chapter 5 is an analysis of various strain measurements collected during FWD and truck testing. Finally, Chapter 6 presents an overall summary of the research study and the appropriate findings.

CHAPTER 2

REVIEW OF LITERATURE

1. INTRODUCTION

This chapter provides an overview of some of the contemporary topics in the design and evaluation of flexible pavements with an emphasis on their relationship to instrumented pavement testing. The discussion begins with a brief explanation of mechanistic-empirical analysis which provides the impetus for strain measurement in flexible pavements. Next, a common analytical method (linear elastic analysis) used to calculate the critical response parameters of mechanistic-empirical analysis is presented. This includes the methodologies used to estimate the input parameters needed to predict pavement response. Finally, a review of previous instrumented flexible pavement tests is presented. Some of the various test facilities are characterized and the results from a sample of the testing conducted at a few of these facilities are examined. The chapter ends with a comparison of contemporary strain measurement techniques.

2. MECHANISTIC-EMPIRICAL ANALYSIS

A pavement structure should be designed so that it will survive the required design life given the many complex elements of the pavement's "operating" environment. Some of these elements are discussed in the *AASHTO Guide for Design of Pavement Structures*. [5] Additionally, the pavement should be the most cost effective given some form of life cycle costing. In general, the mechanistic-empirical approach provides an improvement over purely empirical methods. [5, 6] This is especially true for pavement rehabilitation decisions that are based on the structural capabilities of the existing pavement. [6] The advantages of a mechanistic-empirical approach presented in the *WSDOT Pavement Guide* [7] include the following.

1. Accommodation of changing load types.
2. Better utilization of in situ materials.
3. Better relationship between material properties and actual pavement behavior and performance.
4. Improved definition of existing pavement layer properties.

In addition to use in pavement design and rehabilitation issues, the mechanistic-empirical method can also be used as an analytical tool in at least two other valuable scenarios. [5] First, it can be used to evaluate the performance and life of the pavement based on "what if" analysis. An example would be to analyze the effect of increasing tire pressure or axle loads on pavement life. Second, it can be used to enhance required maintenance and rehabilitation predictions based on site specific changes in design criteria. For example, the mechanistic-empirical method could be used to predict the need for an overlay because of an increase in ESAL's over the design condition.

The mechanistic-empirical method contains two basic steps. [6]

1. Calculation of the critical pavement response parameters in each pavement layer using some analytical method.
2. Prediction of the resulting pavement performance using established empirical relationships between the response and distress (such as fatigue cracking or rutting).

It should be pointed out however, that this design method is not a recent development. Dorman and Metcalf [8], in 1965, presented design curves based on limiting tensile strain in the AC layer and vertical compressive strain in the subgrade.

3. CRITICAL PAVEMENT RESPONSES

In general, the critical responses for flexible pavements are as follows. [7]

1. Vertical surface deflection.
2. Horizontal tensile strain at the bottom of the asphalt concrete layer.
3. Vertical compressive strain at the top of the granular base.
4. Vertical compressive strain at the top of the subgrade.

The locations of these responses relative to a pavement structure and load are illustrated in Figure 2. Fatigue (alligator) cracking is predicted from the horizontal tensile strain at the bottom of the AC layer. Rutting is attributed to vertical compressive strain at the top of the subgrade. [7]

4. LAYERED ELASTIC ANALYSIS

One of the most common analytical methods used to calculate these critical responses is multi-layered elastic analysis. [7] Layered elastic analysis requires several simplifying assumptions for computational purposes. [9]

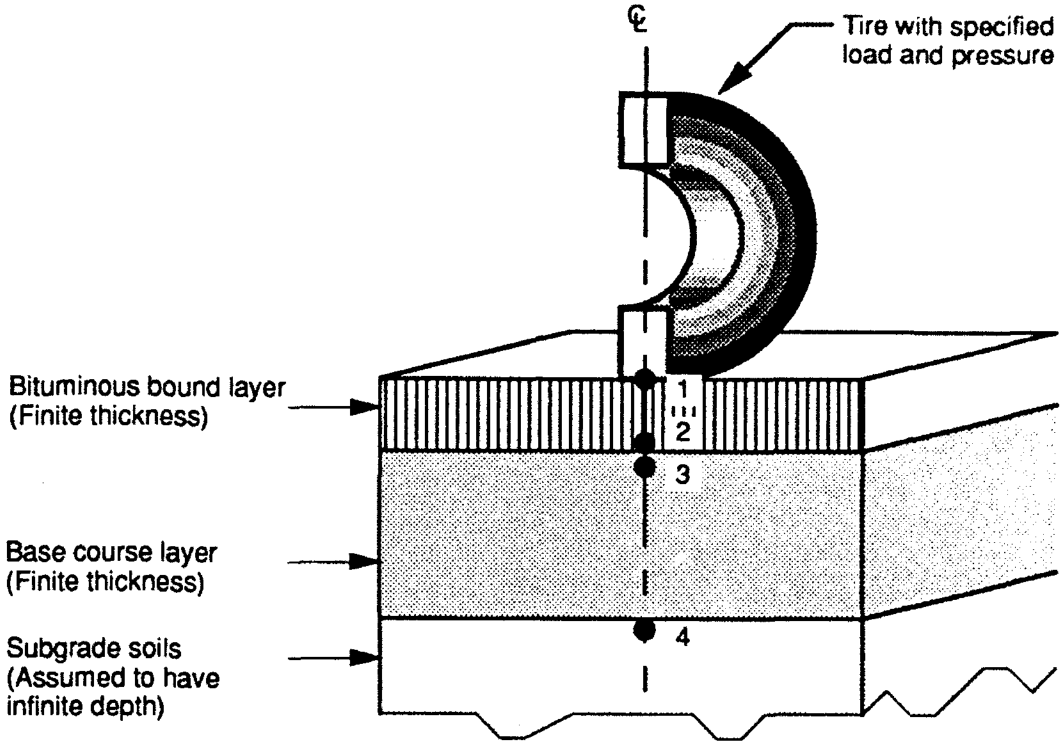
1. Material properties in each layer are homogeneous (elastic properties are the same at all points in the layer).
2. Material properties in each layer are isotropic (elastic properties are the same in all directions at any point).
3. Each layer has a finite thickness except the lowest layer and all are infinite in the lateral direction.
4. The elastic modulus and Poisson's ratio are constant and are known for each layer.

5. ESTIMATING POISSON'S RATIO AND LAYER MODULUS

Through extensive laboratory testing, typical values of Poisson's ratio for the materials found in flexible pavements have become widely accepted. [7]

MATERIAL	POISSON'S RATIO (μ)
Asphalt Concrete	.35
Crushed Stone	.40
Soils (fine-grained)	.45

There are two basic approaches to estimating the elastic moduli for each of the pavement layers. One is laboratory testing. For existing pavements, lab testing is generally considered as "destructive" testing because the pavement structure must be disturbed in order to obtain test samples. The other is nondestructive testing via backcalculation from field deflection data. [7] When estimating in situ material



1. Pavement surface deflection
2. Horizontal tensile strain at bottom of bituminous layer
3. Vertical compressive strain at top of base
4. Vertical compressive strain at top of subgrade

Figure 2. Pavement Response Locations Used in Evaluating Load Effects [7]

properties of an existing pavement structure, backcalculation is a very practical and efficient method. Nondestructive testing offers four general advantages. [6]

1. It is not necessary to damage the pavement in order to perform the test.

2. The time needed to collect and analyze the data required to estimate the material properties is reduced.

3. The in situ conditions of the materials and the characteristics of actual wheel loads can be simulated.

4. Using a FWD, an average of 30 test locations an hour can be tested. [10] The reduced personnel requirements and speed of testing generate cost savings over extended lengths of roadway.

6. BACKCALCULATION OF LAYER MODULI

Backcalculation software normally uses layered elastic analysis to evaluate the deflection basin generated at the pavement surface by a FWD. The backcalculation process "calculates" a deflection basin that matches the measured basin by the FWD (see Figure 3). The matching process is iterative and convergence is assumed to have occurred when a measure of the difference between the computed and measured basins is less than some tolerable error. The layer moduli required to generate the deflection basin are then determined. [7] Figure 4 illustrates this procedure. From these layer moduli, the backcalculation program then calculates the critical responses discussed above.

Ullidtz compared the pavement response generated by a FWD load to that of a heavy truck wheel moving at approximately 40 mph. [6] Further, he found that the stress conditions generated by the two loads were very similar and concluded that ". . . if the deflection basin is measured under an FWD test and the theory of elasticity is then used to determine those moduli of the individual layers that would produce the same deflection basin, then the resulting layer moduli will be representative of the pavement materials under heavy traffic loading." [6]

To compute the pavement response to loading using layered elastic analysis, the thickness of each pavement layer and loading condition must also be known. The loading

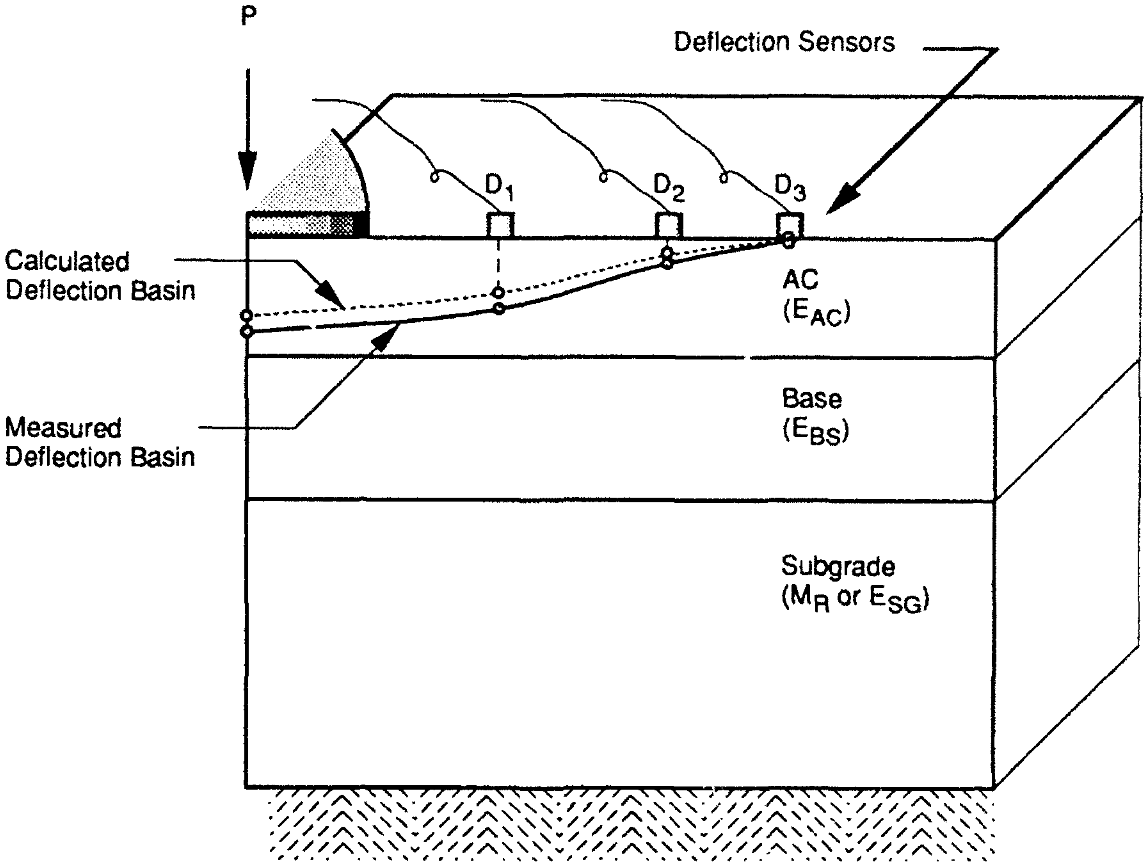


Figure 3. The Backcalculation Process - Matching Measured and Calculated Deflection Basins [7]

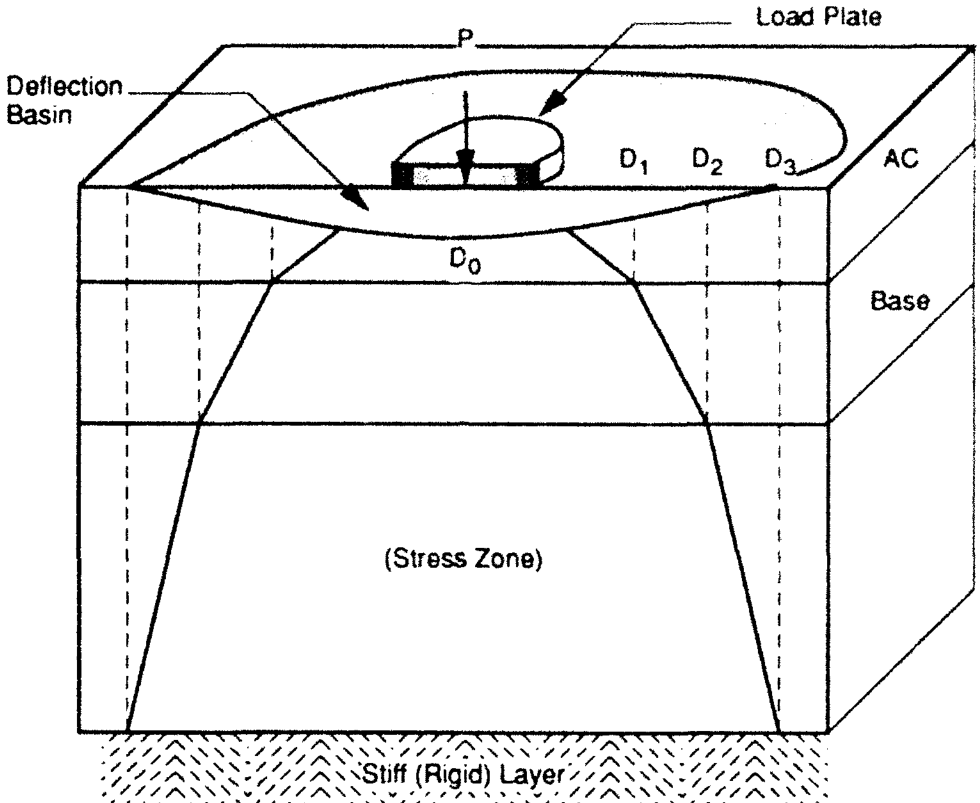


Figure 4. Illustration of Backcalculation to Estimate Layer Moduli [7]

conditions are defined by the magnitude, geometry, and number of loads. [7] The magnitude of the load is the total force (P) applied to the pavement surface. Load geometry is represented as the radius (r or a) of the circle determined by the contact pressure (p) and magnitude (P). While most wheel loads are more elliptical than circular, the differences in analysis are regarded as negligible. [7] Figure 5 illustrates the layered elastic model of a pavement structure and the applied load.

6.1 Accuracy and Consistency of Backcalculated Moduli

In order to obtain reasonable results from layer elastic analysis the pavement layers must be characterized accurately. [11] Backcalculation assumes that the layer moduli generated when the calculated surface deflections match the measured deflections are representative of the pavement structure. The goal is to gain a reasonable assessment of the pavement. A perfect prediction is unnecessary. Often, it is necessary to have a basic understanding of the pavement being evaluated in order to properly assess the output of the backcalculation process. [12] Variability in any aspect of the analysis can affect the estimated structural capacity of the pavement system. According to Hossain and Zaniewski this variability is affected by equipment repeatability and the spatial characteristics of the pavement structure. [13] Chou and Lytton [12] describe the potential causes of analysis error as random and systematic. Random error includes both equipment repeatability and spatial characteristics of the pavement structure. Systematic errors involve any deviation between the theoretical model and actual pavement behavior. This type of error also includes any incorrect assumptions pertaining to material characteristics and layer thicknesses. [12] Hossain and Zaniewski [13] support the conclusion drawn by Mamlouk et al. that ". . . equipment variability is insignificant compared to spatial variability."

The systematic error discussed by Chou and Lytton is a valid concern but difficult to assess during routine pavement analysis. In fact, Uzan et al. [14] demonstrated that

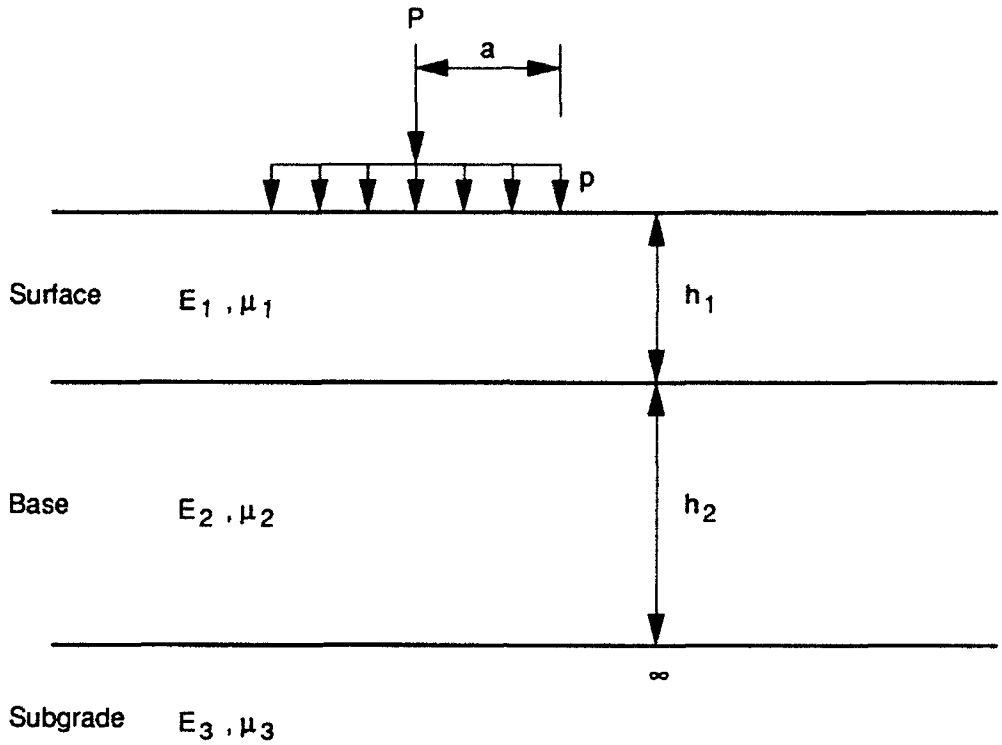


Figure 5. Layered Elastic Pavement Model [7]

linear and nonlinear analyses produce comparable backcalculated layer moduli for pavements with surface course thicknesses greater than five inches. Measurable spatial variability should be the major concern.

6.1.1 Spatial Variability

Spatial variability is affected by how homogenous and isotropic the pavement structure is along its length. One way to account for this variability is to conduct the optimal frequency of FWD tests along a given section of the pavement. Based on their experience in the state of Arizona, Hossain and Zaniewski [13] have suggested that a "viable" number of FWD tests for sections over one mile in length is 5 per mile. For shorter sections (up to 90 feet in length) the number of FWD tests did not affect the estimated structural capacity.

Spatial variability is also affected by the variation in the thicknesses of the pavement layers along the length of the pavement section. Recently, there have been numerous attempts to determine layer thicknesses from FWD deflection data. No single method has received widespread support. The Federal Highway Administration (FHWA) is also experimenting with the use of ground penetrating radar to determine pavement layer thicknesses. [15] This technology shows promise but its widespread use by highway and transportation agencies is uncertain at this time.

At present, the most common methods for determining layer thicknesses (other than "as built" data) are coring and boring. Coring is used to evaluate the surface layer. Boring is more oriented to the evaluation of base, subbase, and subgrade layers. For some states coring is a routine requirement for pavement rehabilitation. For project rehabilitation design in Washington State, two to five core samples are obtained if FWD deflection data is collected. If deflection data is not obtained, the required sampling frequency varies from every 500 to 2000 feet. [16]

Boring is another matter, however. Boring is relatively expensive for any project of modest length. Normally, it is done only when there is great uncertainty in the material properties and characteristics of the pavement being evaluated. This is unfortunate, given that the quality of backcalculation results is greatly affected by accurate layer thicknesses.

6.1.2 Effect of a Stiff Layer Condition [17]

Recently, the thickness of the subgrade layer has received much emphasis. In particular, the effect of an apparent stiff layer at some depth in the subgrade on layer moduli has become of great interest. It is widely accepted that the depth to a stiff layer has a significant impact on backcalculated layer moduli, especially when the depth is relatively shallow (10-20 feet). [12, 17, 18, 19, 20] Traditionally, such layers were felt to be needed either due to a rock layer or stress sensitive materials. [19, 21]

The problem of routinely performing backcalculation without recognizing the effects of a stiff layer condition are well known. Often, no information is available that would suggest a stiff layer condition is present. However, in many instances backcalculation results suggest that inclusion of a stiff layer at some depth results in more realistic moduli. An example of this situation was presented by Mahoney et al. [22] which demonstrated that the base and subgrade moduli are "inverted" ($E_{sg} > E_{base}$) when a stiff layer condition is not used. Engineering judgment would suggest that such inverted moduli are, in general, unrealistic.

These inverted moduli are a result of the "compensating effect" provided by the layers in the pavement to ensure that the calculated surface deflections match the measured surface deflections. [13] The net effect is that the modulus of the subgrade is increased from its "actual" value in order to compensate for the relative stiffness provided by the stiff layer which was not included in the analysis. Even though the overall structural capacity of the pavement does not change individual layer moduli can be off by as much as 50 percent. As a result, the calculated values of the critical pavement responses used in mechanistic-empirical design can be "far from the truth." [23] For mechanistic-empirical design accurate layer moduli are the means to an end. Even though the strains are of more relative importance than the layer moduli in mechanistic-empirical design [24], accurate layer moduli must be determined if one is to calculate realistic pavement response parameters. An example will be provided in Chapter 3. Naturally, this raises questions about how to locate the depth of such stiff layers and how stiff should they be?

6.1.2.1 Load and Geostatic Stresses. The need for stiff layers within the subgrade domain can certainly be due to rock layers or extremely stiff soils such as some glacial tills. However, there are other conditions, not so immediately apparent, which warrant the use of a stiff layer within the subgrade. Typical stresses in the subgrade due to an applied load and geostatic conditions demonstrate one such condition. Mahoney et al. [22] have also provided an example of this.

By use of the ELSYM5 computer program, the vertical and horizontal stresses were estimated under a 9,000 lb. load with a 100 psi contact pressure. Comparing the stress caused by the load to that caused by the weight of the soil (geostatic) it is apparent that the geostatic stresses are dominant and can be rather large even at a depth of 10 feet. For the example presented by Mahoney et al. [22], the horizontal geostatic stress at 10 feet was 20.7 psi while the horizontal stress due to the surface load was nonexistent. This implies that the combination of these geostatic stresses and stress sensitive subgrades can result in a stiff layer condition even at shallow depth. The next question to address is how deep might such layers be, or more specifically, how can the depth to a stiff layer be estimated?

6.1.2.2 Estimation of Stiff Layer Depth. Recent literature provides at least two approaches for estimating the depth to stiff layer (Rohde and Scullion [20], Hossain and Zaniewski [18]). Use of either procedure would assume more specific stiff layer indications (say, from a boring log) are not available, which seems to be a common situation. The approach used by Rohde and Scullion [20] will be summarized below. There are three reasons for this selection: (1) initial verification of the validity of the approach is documented, (2) the approach is used in MODULUS 4.0 — a backcalculation program widely used in the U.S., and (3) the approach was adopted for use in the EVERCALC program. EVERCALC is the backcalculation program used in the analysis portion of this study.

6.1.2.2.1 ***Basic Assumptions and Description.*** A fundamental assumption is that the measured pavement surface deflection is a result of deformation of the various materials in the applied stress zone; therefore, the measured surface deflection at any distance from the load plate is the direct result of the deflection below a specific depth in the pavement structure (which is determined by the stress zone). This is to say that only that portion of the pavement structure which is stressed contributes to the measured surface deflections. Further, no surface deflection will occur beyond the offset (measured from the load plate) which corresponds to the intercept of the applied stress zone and the stiff layer (the stiff layer modulus being 100 times larger than the subgrade modulus). Thus, the method for estimating the depth to stiff layer assumes that the depth at which zero deflection occurs (presumably due to a stiff layer) is related to the offset at which a zero surface deflection occurs. This is illustrated in Figure 6 where the surface deflection D_C is zero.

An estimate of the depth at which zero deflection occurs can be obtained from a plot of measured surface deflections and the inverse of the corresponding offsets $\left(\frac{1}{r}\right)$. This is illustrated in Figure 7. The middle portion of the plot is linear with either end curved due to nonlinearities associated with the upper layers and the subgrade. The zero surface deflection is estimated by extending the linear portion of the D vs. $\frac{1}{r}$ plot to a

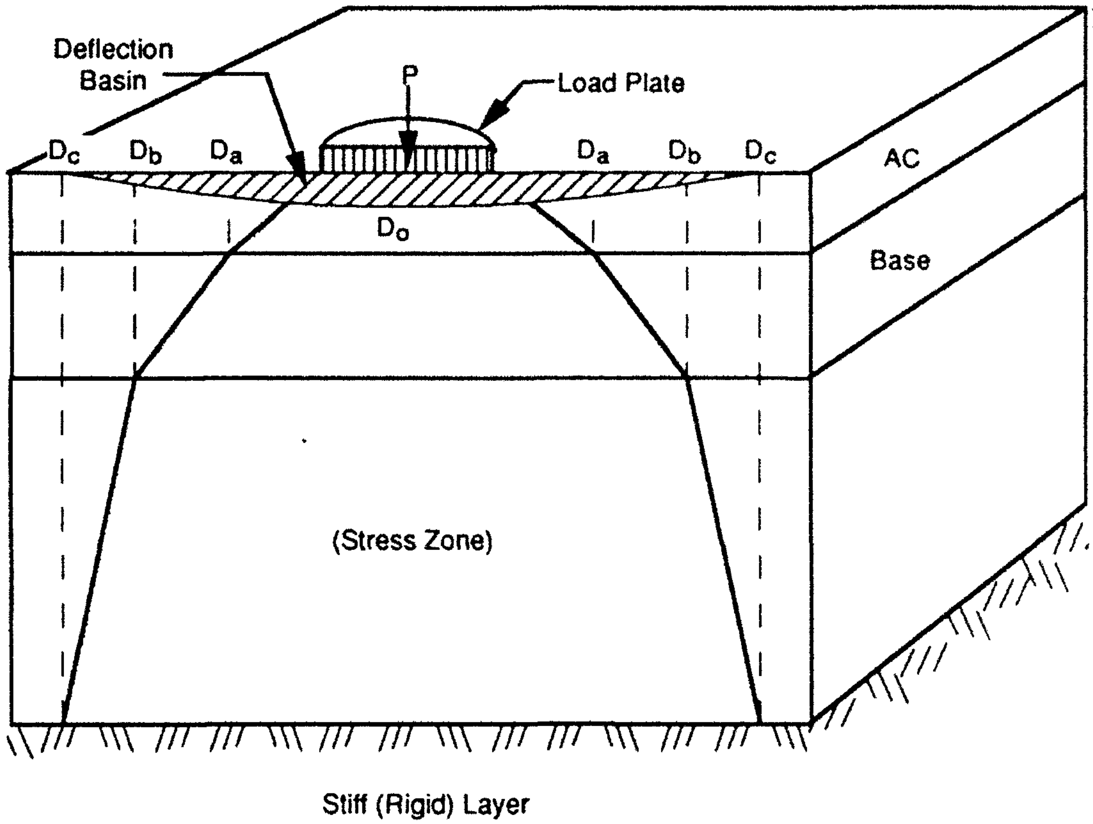


Figure 6. Illustration of Zero Deflection Due to a Stiff Layer [17]

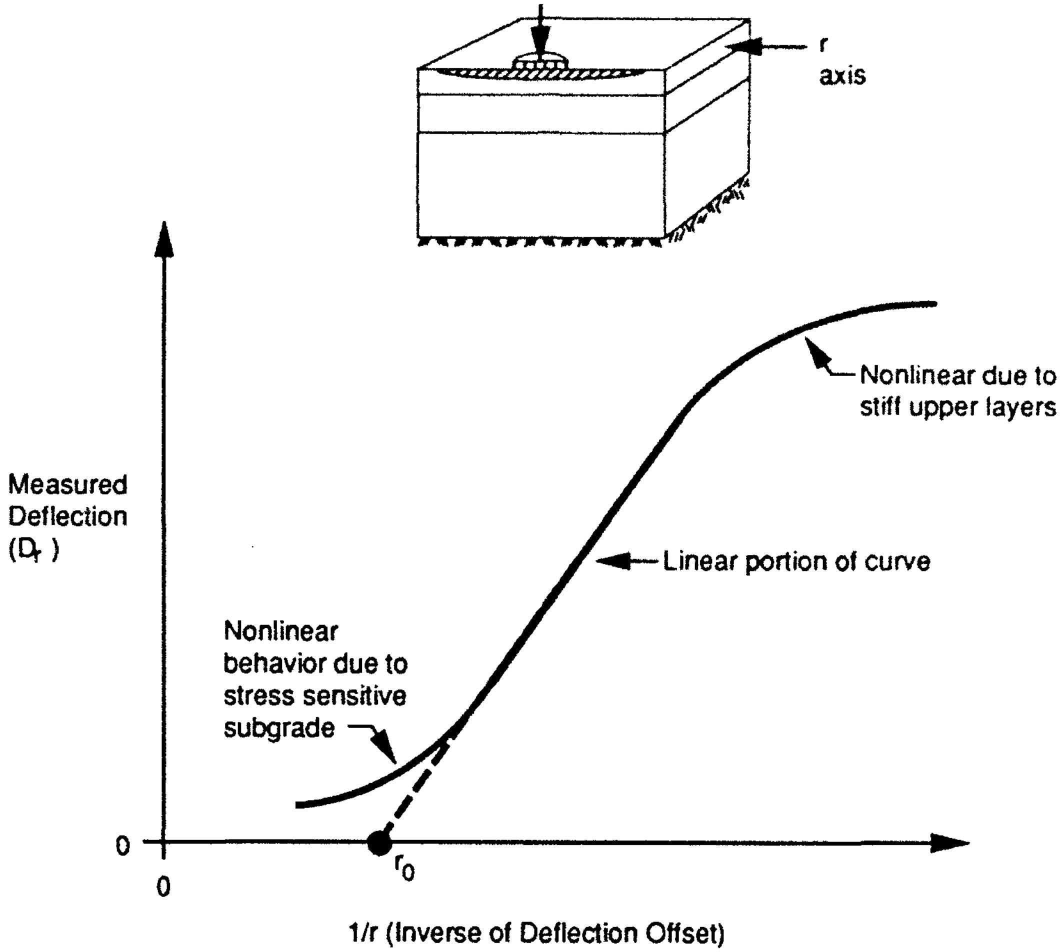


Figure 7. Plot of Inverse of Deflection Offset vs. Measured Deflection [17]

$D = 0$, the $\frac{1}{r}$ intercept being designated as r_0. Due to various pavement section-specific factors, the depth to stiff layer cannot be directly estimated from r_0 — additional factors must be considered. To do this, regression equations were developed based on BISAR computer program generated data for various levels of the following factors:

- Load = 9000 lb
- Moduli ratios
  - E_1/E_{sg}
  - E_2/E_{sg}
  - E_{stiff}/E_{sg}
- Layer thicknesses
  - Surface layer
  - Base layer
  - Depth to stiff layer measured from the pavement surface

Four separate regression equations were reported by Rohde and Scullion [20] for various levels of AC layer thickness. The dependent variable is $\frac{1}{B}$ (where B is the depth to the top of the stiff layer measured from the pavement surface) and the independent variables are r_0 (which is the 1/r intercept as shown in Figure 7) and various deflection basin parameters. The equations are:

(1) AC less than 2 in. thick

$$\frac{1}{B} = 0.0362 - 0.3242\,(r_0) + 10.2717\,(r_0^2) - 23.6609\,(r_0^3) - 0.0037\,(BCI)$$

(2) AC 50 to 2 to 4 in. thick

$$\frac{1}{B} = 0.0065 + 0.1652\,(r_0) + 5.4290\,(r_0^2) - 11.0026\,(r_0^3) + 0.0004\,(BDI)$$

(3) AC 4 to 6 in. thick

$$\frac{1}{B} = 0.0413 + 0.9929\,(r_0) - 0.0012\,(SCI) + 0.0063\,(BDI) - 0.0778\,(BCI)$$

(4) AC greater than 6 in. thick

$$\frac{1}{B} = 0.0409 + 0.5669\,(r_0) + 3.0137\,(r_0^2) + 0.0033\,(BDI) - 0.0665\log\,(BCI)$$

where r_0 = $\frac{1}{r}$ intercept (extrapolation of the steepest section of the D vs. $\frac{1}{r}$ plot) in units of $\frac{1}{ft}$,

SCI = $D_0 - D_{12"}$, Surface Curvature Index,

BDI = $D_{12"} - D_{24"}$, Base Damage Index,

BCI = $D_{24"} - D_{36"}$, Base Curvature Index,

D_i = surface deflections (mils) normalized to a 9,000 lb. load at an offset i.

6.1.2.2.2 ***Confirmation of Stiff Layer Depths.*** Data provided to Mahoney et al. [17] by Mr. Bertil Mårtensson of RST Sweden AB during 1992 provided the initial confirmation of the Rohde and Scullion [20] stiff layer calculation (other than reported by Rohde and Scullion). These results provided by Mårtensson are shown in Figure 8. The road (Route Z-675) is located in south-central Sweden. The <u>field</u> measured depths were obtained by use of borings and a mechanical hammer. The hammer was used to drive a drill to "refusal" (similar to the standard penetration test (SPT)). Thus, the measured depths could be bedrock, a large stone, or hard till (glacially deposited material); however, this is an area where rock is commonly encountered at relatively shallow depths. Further, the field measured depths were obtained independently of the FWD deflection data (time difference of several years).

The FWD deflections were obtained with a KUAB 50 with deflection sensor locations of 0, 7.9, 11.8, 17.7, 23.6, 35.4, and 47.2 in. from the center of the load plate. The equations by Rohde and Scullion [20] were used to calculate the depth to stiff layer. Since the process requires a 9000 lb. load and 1 ft deflection sensor spacings, the measured deflections were adjusted linearly according to the ratio of the actual load to a 9000 lb. load.

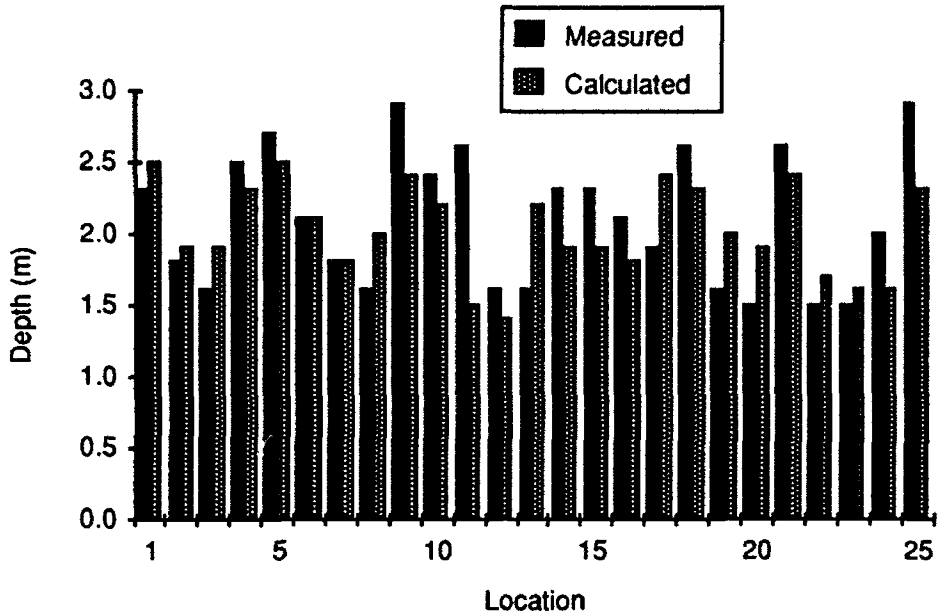


Figure 8. Plot of Measured and Calculated Depths to Stiff Layer for Road Z-675 (Sweden) [17]

This initial confirmation resulted in the addition of the Rohde and Scullion [20] equations to the program EVERCALC, which is the backcalculation software used by WSDOT. [22]

7. FLEXIBLE PAVEMENT TEST FACILITIES

Wester [25] noted that L.W. Nijboer performed the first comparison of calculated and measured strain values in AC pavements in the Netherlands in 1955.

> "This very promising first experiment was the start in developing techniques to measure, under actual conditions, the strain at various levels in a bituminous bound layer and at the interface between the bituminous layer and the unbound base or sub-base." [25]

In Nijboer's study the surface strains were measured using elastic resistance strain gauges mounted on the pavement surface. The results showed "relatively good agreement" between the measured and calculated strain values. [25]

Over the past 38 years since Nijboer's work there have been numerous other attempts to design, construct, operate, and validate other AC pavement test facilities. In general, the purpose of these facilities is to examine the correlation between theory and what happens in real pavements under actual loads. [26]

7.1 Characterization of Various Test Facilities [27]

Test facilities with controlled construction and some form of accelerated loading provide several advantages. Specifically, they allow relatively complete control over test parameters, repeatability of testing conditions, and the ability to apply a large number of loads in a relatively short period of time. [27] Of course, test roads with retrofitted instrumentation and actual vehicular loading provide the opposite scenario. They provide an environment closer to in-service conditions but they sacrifice the experimental control found in controlled test tracks.

The various test facilities can be divided into three basic groups [27]:

1. Linear Test Tracks

2. Circular Test Tracks
3. Test Roads with controlled or uncontrolled loading

Sebaaly et al. [27] provided a thorough description of the prominent test facilities in each of the three groups.

Most of the test facilities have been designed and built as true "test" sections where the construction was controlled to allow instrumentation to be installed during the construction phase. Only a relatively small number of experiments have been conducted using instrumentation retrofitted into an existing pavement and applying actual truck loads. Additionally, the loading was usually applied by some form of accelerated loading device. Accelerated loading devices (ALD's) are of basically two types: circular and linear. Generally speaking, circular ALD's are restricted to operation at only one pavement facility and linear ALD's are capable of being transported to various test locations including in-service pavements. This is not to say that circular ALD's can not be moved. Some of the circular ALD's can be moved from one test pavement to another at the same facility to allow testing and construction to occur simultaneously.

7.2 Comparisons of Measured and Calculated Strains from Various Flexible Pavement Experiments

A review of the published research from flexible pavement test facilities shows numerous examples of acceptable agreement between measured and calculated strains in bituminous layers. A summary of these tests is contained in Table 1, which is not a complete list but rather a representative sample. The number of tests conducted that result in unacceptable agreement between measured and calculated strains is unknown. A discussion of the specific results from a sample of the tests in Table 1 follows.

In 1967, Nijboer [26] compared the strains measured under a single wheel load (2804 to 4847 lbs) on State Highway 1 in the Netherlands to those calculated using Burmister's two layer solution (partial results are summarized in Tables 2 and 3). Radial strain at the surface and bottom of a 7.5 inch layer of AC was measured using strain

Table 1. Summary of Various Instrumented Flexible Paven.ent Tests

Reporting Agency (Reference)	Test Location	Type of Facility	Type of Strain Instrumentation	Strain Responses Measured	Pavement Structure (inches)	Type of Loading for Testing	Load Magnitude (pounds)	Source of Theoretical Computation	Year of Testing	Exposed to Normal Traffic
California Division of Highways (Zube [4])	Northern California	Linear Test Track and Test Road	SR-4 strain gauges glued to surface or placed in carrier block	Transverse at surface and bottom of AC	Six Total Sections 1: AC 3.75, BS 8.0 (CTB) 2: AC 6.75, BS 6.0 3: AC 3.75, BS 12.0 4: AC 3.0, BS 9.0 5: AC 3.0 New plus 2.0 Old, BS Variable 6. AC 2.0, BS 4.0	Duals and super single - 2 axle truck	5000 to 9000 per wheel	Boussinesq equations	1963	Yes
Dutch Road Research Centre (Nijboer [26])	Highway 1	Test Road	Strain gauge attached to a thin slab of sand asphalt	Radial at surface and bottom of AC	AC: 7.5 BS: None	Single wheel loads	2804 to 4847	Burmister 2 - layer	1967*	Yes
Shell Laboratory (Gusfeldt [29])	Hamburg, Germany	Linear Test Track	Gauge stuck to asphalt carrier block	Radial strain at various depths in AC	AC: 5.5 BS: 33.9	Linear test apparatus (single tire)	880 to 4400 per wheel	Jones' tables of stresses in 3 layer elastic system	1967*	No
Shell Research N.V. (Klomp [30])	Highway 1	Test Road	600 ohm electrical resistance	Horizontal at surface and various depths in AC (0-5.5 in.)	AC: 1.2 BS: 6.7 (ATB)	Single front wheel of a loaded truck	2818 to 4862 per wheel	Jones' tables of stresses in 3 layer elastic system	1967*	Yes
Shell Laboratory (Dempwolff [28])	Hamburg, Germany	Linear Test Track	Wire gauges glued into asphalt carrier blocks	Transverse and Longitudinal at various depths in the AC	AC: 8.7 Section I (Dense) Section II(Open) BS: 11.8	Linear test apparatus (single tire)	1100 to 4400 per wheel	BISTRO	1967-69 1972*	No
Nihon Univ, Japan (Miura [31])	Tomei Highway (between Tokoyo and Nagoya)	In service pavement	Electric resistance gauges molded by epoxy and polyester resin	Transverse and Longitudinal at various depths in the AC	AC: 3.9 BS: 7.1 (ATB) SB: 6.7 (CTB)	Dual wheel loads	6600 to 15,400 per wheel	Burmister (single and dual circular loading)	1972*	Yes
National Institute for Road Research, South Africa (Freeme [11])	Special Road 12/2, South Africa	In service pavement	Strain meters developed by Road Research Lab in the UK	Tensile strain at the bottom of the AC	AC: 1.0, 2.0, 3.9 (Dense and Open Grade) BS: 11.8 SB: 3.9 (LTB)	2 axle single wheel truck	2565 to 8370 per wheel	Chevron computer program	1972*	Yes

Table 1. Summary of Various Instrumented Flexible Pavement Tests (continued)

Reporting Agency (Reference)	Test Location	Type of Facility	Type of Strain Instrumentation	Strain Responses Measured	Pavement Structure (inches)	Type of Loading for Testing	Load Magnitude (pounds)	Source of Theoretical Computation	Year of Testing	Exposed to Normal Traffic
Koninklijke/Shell -Laboratorium (Valkering [32])	E8 Motorway, Netherlands	Trial Section	Strain gauge type not reported	Longitudinal and transverse at surface and transverse at 2.8 in depth	Section I AC: 8.3 BS: 7.1 (CTS) Section II AC: 11.0 BS: None	Wheel of a skid measurement system	450	BISAR	1972*	Yes
Royal Military College; Ontario Ministry of Transportation and Communication; Gulf Canada, Ltd.; Univ of Waterloo (Halim [33])	Royal Military College, Kingston	Test Pit	Foil type gauges bonded to top and bottom of plastic mesh; Mastic strain carriers (ARC) with two 120 ohm gauges embedded in mastic plate	Horizontal tensile strains at mesh and bottom of AC	AC: 4.5 to 9.8 (with and without plastic mesh) BS: None SG: Dry and saturated	12 in. diameter rigid circular plate	2250 to 9000	BISAR	1983*	No
Laboratoire Central des Ponts et Chaussées (LCPC) (Autret [34])	Nantes, France	Circular test track	H-gauges glued to aluminum or plexiglass backing	Horizontal strain at bottom of AC and vertical strain at top of SG	Ring B_0, Section 1 AC: 2.0 BS: 17.7	Accelerated loading device (ALD) with 4 half axles	22,500 and 29,250 per axle	ALIZE III computer program	1984	No
Organization for Economic Cooperation and Development (OECD) (Scazziga [35])	Nardò, Italy	Linear test track	H-gauges, gauges glued into carrier blocks, core gauges	Horizontal strain at a depth of 2.0 in. and at bottom of AC	AC: 5.1 BS: 6.7	2 axle truck	Front axle: 12,155 Rear axle: 25,636	Method of Equivalent Thickness (MET)	1984	No
FHWA (Bonaquist [36])	Turner-Fairbank Highway Research Facility	Linear test track	Gauge type not reported	Surface and bottom of AC	Lane 1 AC: 5.0 BS: 5.0 Lane 2 AC: 7.0 BS: 12.0	Linear ALF (one half of a dual tire single axle)	9400, 14,100 and 19,000 per half axle	ELSYM5	1988*	No
Ministry of Transport, The Netherlands (Dohmen [37])	Road and Railroad Research Laboratory	Linear test track	Dynatest strain transducer and TML embedment gauges	.3 inches above bottom of AC	AC: 4.7, 7.1, and 9.4 BS: None	FWD	11,250	BISAR	1992*	No
Dutch Team, FORCE Project, OECD [38]	LCPC, Nantes, France	Circular test track	TML embedment strain gauges	Radial strain at bottom of AC	AC: 5.5 BS: 11.0	ALD (half axle)	12,938 per half axle	BISAR	1989 1991*	No

Table 1. Summary of Various Instrumented Flexible Pavement Tests (continued)

Reporting Agency (Reference)	Test Location	Type of Facility	Type of Strain Instrumentation	Strain Responses Measured	Pavement Structure (inches)	Type of Loading for Testing	Load Magnitude (pounds)	Source of Theoretical Computation	Year of Testing	Exposed to Normal Traffic
Ministry of Transport, The Netherlands (Dohmen [37])	LCPC, Nantes, France	Circular test track	TML embedment gauges	Bottom of AC	Section 01 AC: 4.8 BS: 11.0 Section 02 AC: 5.5 BS: 11.0	FWD	13,500 and 16,875	BISAR	1989 1992*	No
Ministry of Transport, The Netherlands (Dohmen [37])	Road and Railroad Research Laboratory	Linear test track	Gauge type not reported	Longitudinal and transverse at bottom of AC	AC: 5.9 BS: None	FWD	Not reported	3 layer system	1992*	No
Ministry of Transport, The Netherlands (Dohmen [37])	Road and Railroad Research Laboratory	Linear test track	Gauge type not reported	Longitudinal and transverse at bottom of AC	AC: 5.9 BS: None	LINTRACK Super singles and duals (half axle)	11,250 per half axle	BISAR	1992*	No
FHWA (Sebaaly [39])	Pennsylvania Transportation Institute	Linear test track	Dynatest H-gauge Kyowa gauge ARC gauge Core gauge	Bottom of the AC	Thin AC: 6.0 BS: 8.0 Thick AC: 10.0 BS: 10.0	Single drive axle tractor with a tandem axle semitrailer	3760 to 20,820 per axle	PENMOD	1989 1992*	No
Royal Institute of Technology, Sweden (Lenngren[24])	Road and Traffic Laboratory, Finland	Linear test pavement	Core gauges	Horizontal at bottom of AC	Thin Section AC: 3.1 BS/SB: 24.4 Thick Section AC: 5.9 BS/SB: 21.7	FWD	2813, 5626, and 11,250	BISAR and CLEVERCALC	1989 1991*	No
Cambridge Univ. (Hardy [40])	Transport and Road Research Lab	Test section	Metal foil gauges	Transverse at bottom of AC	AC: 7.9 BS: 11.8	Four - axle articulated vehicle	Not reported (based on dynamic load)	Convolution Theory	1992*	No

Notes:

AC = Asphalt Concrete
BS = Base Course
SB = Subbase

CTB = Cement treated base
ATB = Asphalt treated base
CTS = Cement treated sand

SG = Subgrade
LTB = Lime treated base
* = Year reported in literature

Table 2. Comparison of Measured and Calculated Surface Radial Strains — State Highway 1, The Netherlands (after Nijboer [26])

Test Run	Wheel Load (pounds)	AC Modulus (ksi)	Microstrains		Ratio Measured/Calculated
			Measured	Calculated	
1	2804	292	62	109	0.57
2	2804	398	65	88	0.74
3	2804	526	58	68	0.85
4	2804	384	78	74	1.05
5	4847	213	137	165	0.83
6	4847	185	213	189	1.13
7	4827	313	108	126	0.86
8	4827	228	121	164	0.74
11	4827	292	107	131	0.82
18	4827	555	84	82	1.02
19	4827	384	101	112	0.90
20	4430	1920	41	31	1.32
21	4430	1706	35	34	1.03
22	4467	1920	39	32	1.22
23	4467	1706	36	35	1.03
Mean					0.94

Calculated strains according to Burmister.

Table 3. Comparison of Measured and Calculated Radial Strains at the Bottom of the AC Layer — State Highway 1, The Netherlands (after Nijboer [26])

Test Run	Wheel Load (pounds)	AC Modulus (ksi)	Microstrains		Ratio Measured/Calculated
			Measured	Calculated	
1	2804	292	86	85	1.01
2	2804	398	92	68	1.35
3	2804	526	73	53	1.38
4	2804	384	84	67	1.25
5	4847	213	112	145	0.77
6	4847	185	155	136	1.14
7	4827	313	123	112	1.10
11	4827	292	100	118	0.85
18	4827	555	83	80	1.04
19	4827	384	100	110	0.91
20	4430	1920	28	30.5	0.92
21	4430	1706	27	33.5	0.81
22	4467	1920	28	31.5	0.89
23	4467	1706	25	34.5	0.72
Mean					1.01

Calculated strains according to Burmister.

gauges attached to a thin layer of "sand asphalt" and installed during paving. The average ratio of measured to calculated strains was 0.94 at the surface and 1.01 at the bottom of the AC layer.

Dempwolff and Sommer [28] conducted a two year testing program (1967-1969) at the Shell Laboratory test track in Hamburg, Germany. The test track was constructed in two sections. Section 1 was dense graded AC and Section 2 was an open graded hot mix. The AC layer was 8.7 in. thick in both sections. The load (ranging from 1100 to 4400 lbs) was applied by way of a single tire, linear accelerated loading device. Strain responses were measured through wire strain gauges that were glued into asphalt carrier blocks. As can be seen from Table 4, the ratio of measured to calculated strain at the bottom of the AC layer for both sections is quite good (0.9-1.0 for Section 1 and 0.9-1.2 for Section 2). The strains measured at the surface were always larger (35-100 microstrains) than the theoretical values, and as such, the measured to calculated ratios are less than satisfactory. An interesting observation made by Dempwolff and Sommer [28] was that, contradictory to theory, the longitudinal and transverse strains were not equivalent. The transverse strains were larger (5-50 percent) than the longitudinal strains. The authors provided no explanation for this observation. Given the extensive research into contact pressure distribution of loaded truck tires conducted in recent years, such results should be expected. We now know that maximum contact pressures can be as high as two times the inflation pressure. Also, at a constant tire inflation pressure, the contact pressure in the shoulder region of a bias ply tire can increase substantially for a modest increase in tire load. [41]

In 1983, Halim et al. [33] compared measured and theoretical strains in flexible pavements using a test site at the Royal Military College in Kingston, Canada. The main objective of the research was to evaluate the effectiveness of flexible pavements reinforced with a plastic mesh (geogrid). A secondary benefit was the ability to verify or

Table 4. Comparison of Measured and Calculated Strains at the Bottom of the AC Layer — Shell Laboratory Test Track, Hamburg (after Dempwolff and Sommer [28])

	Section I Depth in AC Layer (in.)				Section II Depth in AC Layer (in.)			
	0	2.6	5.5	8.7	0	2.6	5.5	8.7
Measured / Calculated	1.7-2.2	1.8-2.2*	1.4-1.8	0.9-1.0	1.7-2.0	1.8-2.0*	0.8-1.6	0.9-1.2

* Maximum tensile strain measured at temperatures above 25°C.
All strains calculated using BISTRO.

modify elastic layer theory. [33] To conduct this analysis, two foil type strain gauges were embedded in a mastic strain carrier and placed at the bottom of the AC layer. Loads were applied to the test sections through a hydraulic actuator on a 12 inch diameter rigid circular plate. For a load of 9000 pounds the measured and calculated strains at the bottom of the AC compared quite well; a difference of only 3 to 5 percent (see Table 5). However, the comparison at lower load levels using a constant layer modulus (calculated at a 9000 pound load) was progressively worse. To compensate for this effect the authors applied a calibration factor to the layer modulus (the calculation of the calibration factor is discussed in detail in Ref. [33]). The calibration factor (F_p) is the ratio of the elastic modulus of the asphalt or subgrade layer under the load (p) to the elastic modulus at a load of 9000 pounds. The modulus (E_p) for the asphalt or subgrade is then determined by multiplying the modulus at 9000 pounds by the calibration factor. [33] As can be seen in Table 5, this decreased the error in measured and calculated strains by as much as 8 percent.

One of the largest instrumented pavement studies was conducted by the Organization for Economic Cooperation and Development (OECD) Group RTR I2 "Full Scale Pavement Tests". The membership of the group represented 12 countries (see Table 6) and was established in March of 1983. The group had three basic objectives for instrumented pavement testing [35]:

1. To develop and perpetuate a common technical language for pavement testing.
2. To provide a framework for direct comparison of research results across differing nations.
3. Conduct some common pavement tests under the same testing conditions.

In April of 1984, Group RTR I2 conducted a landmark instrumented pavement test. The test was important for two major reasons:

Table 5. Comparison of Measured and Calculated Strains at the Bottom of the AC Layer — RMC Test Pit (after Halim et al. [33])

Load pounds	Calibration Factor Fp	AC Modulus (ksi) Ep = Fp X E4c	Subgrade Modulus (ksi) Ep = Fp X E40	AC Thickness (inches)	Microstrains				
					Measured	Calculated		Error %	
						E4c	Ep	E40	Ep
2250	0.905	184	3.1	6.5	243	179	200	26%	18%
4500	1.000	203	3.4	6.5	358	358	358	0%	0%
6750	1.034	210	3.5	6.5	475	536	518	-13%	-9%
9000	1.000	203	3.4	6.5	680	715	715	-5%	-5%
2250	0.905	127	2.3	7.9	282	191	215	32%	24%
4500	1.000	140	2.6	7.9	475	382	382	20%	20%
6750	1.034	145	2.6	7.9	622	573	555	8%	11%
9000	1.000	140	2.6	7.9	805	765	765	5%	5%
2250	0.905	162	2.0	9.8	122	110	125	10%	-2%
4500	1.000	179	2.2	9.8	217	226	226	-4%	-4%
6750	1.034	185	2.3	9.8	315	330	328	-5%	-4%
9000	1.000	179	2.2	9.8	440	452	452	-3%	-3%

Table 6. Composition of OECD Group RTR 12 "Full Scale Pavement Tests" (after Scazziga [35])

Country Name	Participated In Nardò Experiments
Australia	Yes
Belgium	No
Canada	Yes
Denmark	Yes
Finland	Yes
France	Yes
Germany	Yes
Italy	Yes
Japan	No
Switzerland	Yes
United Kingdom	No
United States of America	No

1. The number and variety of participating organizations (see Table 6). Nine teams from eight member countries installed their own gauges using their own techniques. [35]

2. The variety of strain gauges employed. Seven different gauges representing three gauge groups were installed in the test section (see Figure 9).

The purpose of the test was to compare the instruments and techniques used by member countries to measure the horizontal tensile strain at the bottom of the AC layer generated by the rear axle of a loaded truck. [35]

For ease in comparing measured responses, three of the test conditions were controlled to the extent possible given the nature of such testing. [35]

- <u>Pavement Structure</u>

  The test was conducted on a 131 foot section of an experimental road at the Nardò test facility in southern France. The section consisted of a 5.1 inch AC layer on top of a 6.7 inch crushed stone base. Each team was given about 9.8 linear feet of the section in which to install their instruments.

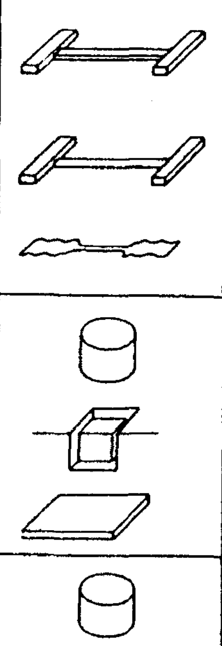
- <u>Applied Load</u>

  There were three almost identical trucks used throughout the testing cycle. These 2 axle trucks had a single tire steer axle and a dual tire drive axle. The axle loads, tire types, and tire pressures were the same for all three trucks and held constant throughout the testing.

- <u>Loading Time</u>

  Truck speed was held reasonably close to 19 mph.

As is common in most field experiments, there were some variables of the testing environment that were either uncontrollable or lacking sufficient control for meaningful comparisons.



GROUP	SCHEMATIC CONSTRUCTION	GAUGE MODEL	ACTIVE LENGTH OF WIRE/ ANCHOR	RESIST- ANCE (Ω)	COST US $	TEAM	ASSEMBLY
1.1		KYOWA KM-120-H2-11L 100-3	70mm/104mm	120 ± 1%	40	3	- FIXATION OF ANCHOR BARS IN THE LABORATORY
		KYOWA KM-120-H2-11L 100-3	70mm/106mm	120 ± 1%	35	5	
		KYOWA KM-120-H2-11L 100-3	70mm/100mm	120 ± 1%	75	7	
1.2		KYOWA KC-70-A1-11	67mm/130mm	120	35	2	- GAUGE GLUED TO SUPPORT AND FIXATION OF ANCHOR BARS IN THE LABORATORY
		PL 30 ou KYOWA KFC-30-C1-11	30mm/100mm	120	23	6	
1.3		HBM DA 3	88mm/140mm	350	180	1	
2.1		HBM LP 21 60-120	60mm/60mm	120	12	1	- GLUED ON MARSHALL SPECIMEN CUT TO 1/3 HEIGHT
		BLH FAE 2-300-35 PL	76mm/76mm	350	35	8	- GLUED ON LABORATORY SPECIMEN
2.2		HBM 20/600 XA21	20mm/20mm	600±0.25	10	9	- GLUED IN THE CENTER OF A LABORATORY SPECIMEN
2.3		METAL FOIL GAUGE	13mm/25mm	120	15	4	- GLUED ON A BLOC OF SHEET ASPHALT
3.1		HBM LP 21 60-120	60mm/60mm	120	12	1	- GLUED ON CORE TAKEN FROM THE PAVEMENT
		HBM 60/600 LP 21		600±0.25	15	3	

Figure 9. Classification of Gauges Installed at the Nardò Test Facility [35]

- Pavement Structure

  Even though the experiment was performed over a relatively short pavement section, there were still significant differences in the pavement structure across the teams' sites (see Figure 10). The AC thickness varied from 4.6 inches to 5.4 inches. The void content was as low as 11 percent and as high as 19 percent. The high void content was due to the special procedures used during paving operations to prevent damage to the gauges. [35]

  To account for this variability several actions were taken. First, BISAR was used to determine the effect (theoretically) of the differing AC layer thicknesses on strain at the bottom of the AC. An 18 percent difference (4.6 to 5.4 inches) equated to only a 5 percent decrease in strain. Additionally, cores were taken from each team's area at the conclusion of testing to accurately determine the layer thicknesses. The difference in the material properties was accounted for by using backcalculated layer moduli from FWD tests conducted at each team's site. [35]

- Pavement Temperature [35]

  The pavement temperature as measured by three teams varied by as much as 18°F. Theoretical analysis using BISAR demonstrated that only a 9°F difference in temperature equaled a 50 percent difference in calculated strain. To account for this, all responses were standardized to 75°F.

- Actual Gauge Location in Reference to the Bottom of the AC [35]

  Once again using BISAR, it was determined that a difference of only 0.2 of an inch could cause a 10 percent difference in measured strain. A 0.8 inch difference equaled a 30 percent error. To solve this potential source of error, the exact position of the gauge in the AC layer was determined.

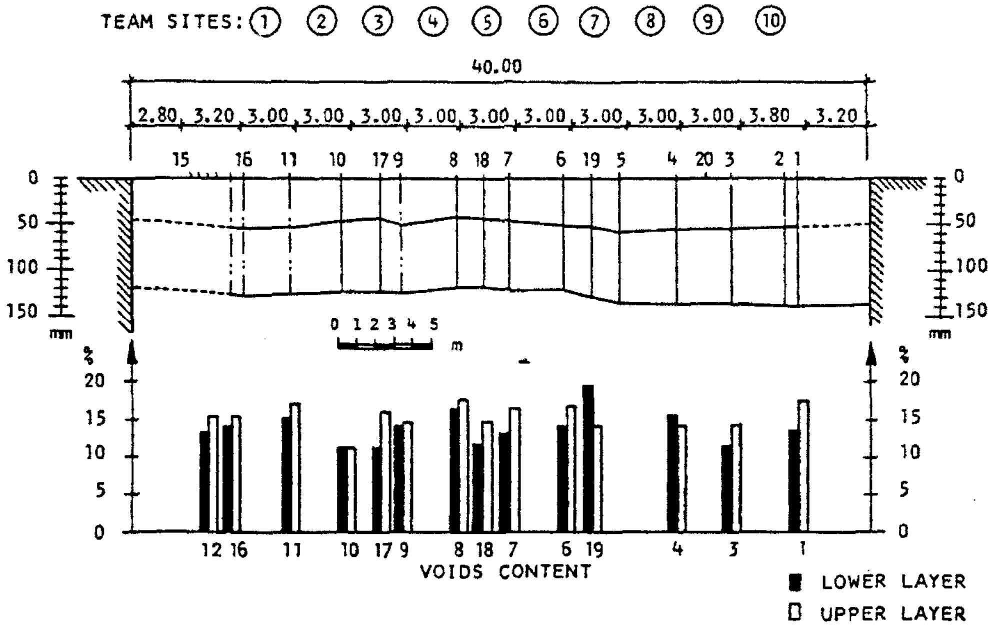


Figure 10. Thickness and Voids Content of the AC Layer—Nardò Test Facility [35]

- <u>Transverse Vehicle Position [35]</u>

  It became obvious during testing that it was virtually impossible to drive the test vehicle over the exact gauge location over repeated test runs (due to driver variability). Calculations with BISAR showed that the maximum strain at the bottom of the AC under the dual wheel load was 50 percent less at a distance of only 2 inches outside the outer wheel. There was no practical solution to account for this potential variability and as such, must be kept in mind when reviewing the results of the experiment.

The results of the experiment are summarized in Figures 11-14. Figure 11 shows the mean and standard deviation of all the strain measurements standardized at 75°F. It appears that some gauges (1.1, 2.2, and 2.3) performed better than others. The variability in the results is attributed to gauge repeatability and truck alignment. [35] In an attempt to reduce the effect of truck alignment the mean and standard deviation of the maximum strains were presented in the same format (Figure 12). The mean of the strain maxima from Figure 12 gives a range of 181 to 357 microstrains. Taking into account varying layer thicknesses and gauge locations, BISAR calculated values ranged from 168 to 263 microstrains. [35] While the range of the measured values is somewhat larger than the theoretical, the mean of all the strain maxima (about 260 microstrains) falls within that theoretical range rather nicely.

The moduli backcalculated from the FWD deflection data were used in the Method of Equivalent Thickness (MET) to calculate the theoretical horizontal tensile strain under a dual wheel load. A comparison of these calculated strains to strains measured during truck testing at a similar pavement temperature is presented in Figure 13. Most of the ratios are within ± 20 percent of equality.

A final comparison is presented in Figure 14. The mean of all maximum strains (adjusted only for temperature) is shown with a range of ± 20 percent. Three sets of data

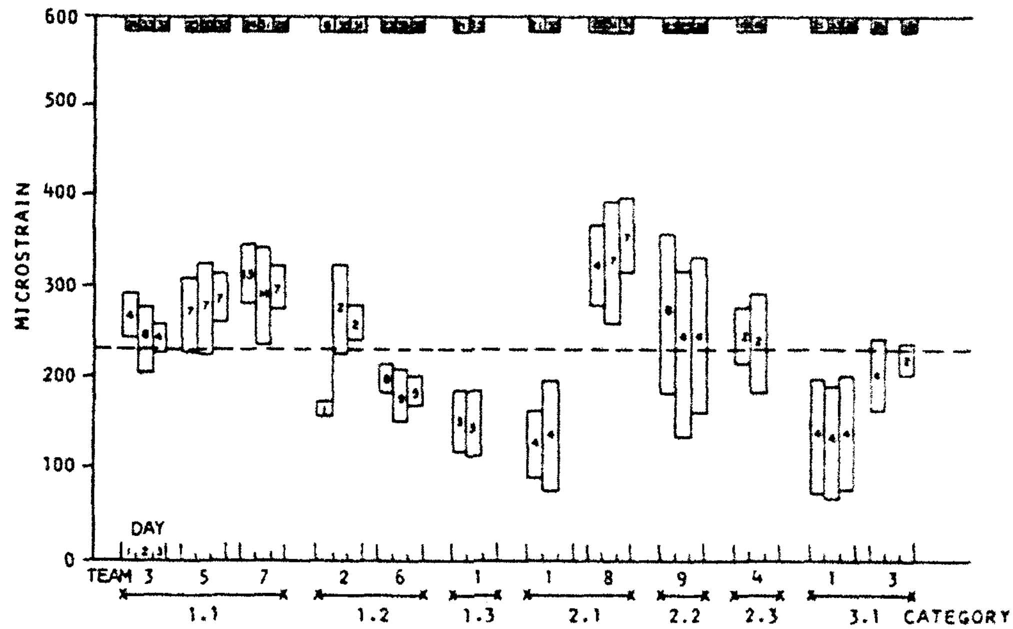


Figure 11. Mean and Standard Deviation of Strain Measurement Results at 75°F, All Gauges, By Day of Measurement, Team and Gauge Category—Nardò Test Facility [35]

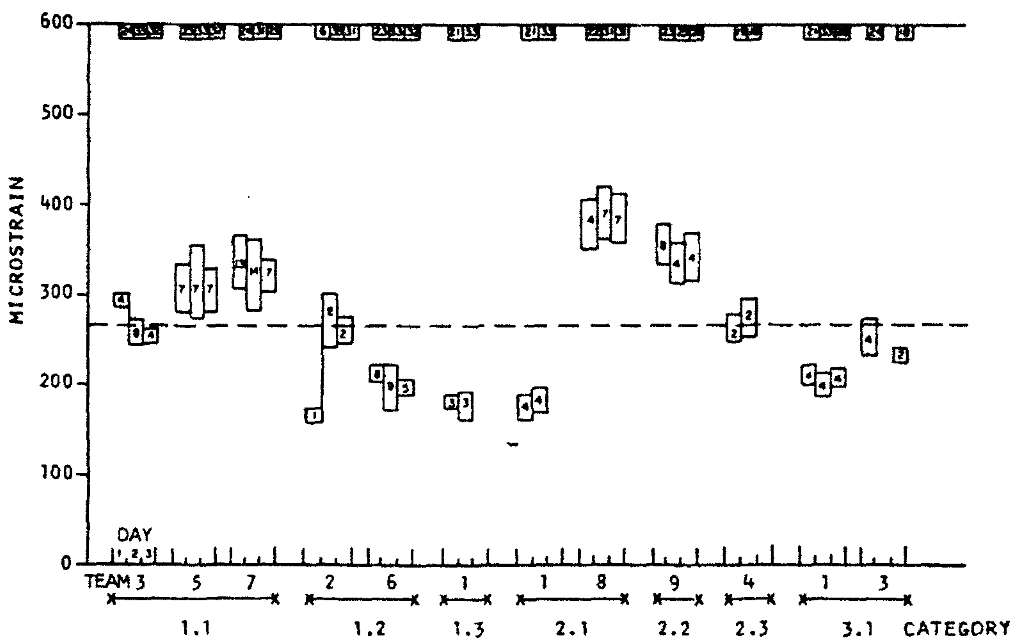


Figure 12. Mean and Standard Deviation of Maximum Strains at 75°F, All Gauges, By Day of Measurement, Team and Gauge Category—Nardò Test Facility [35]

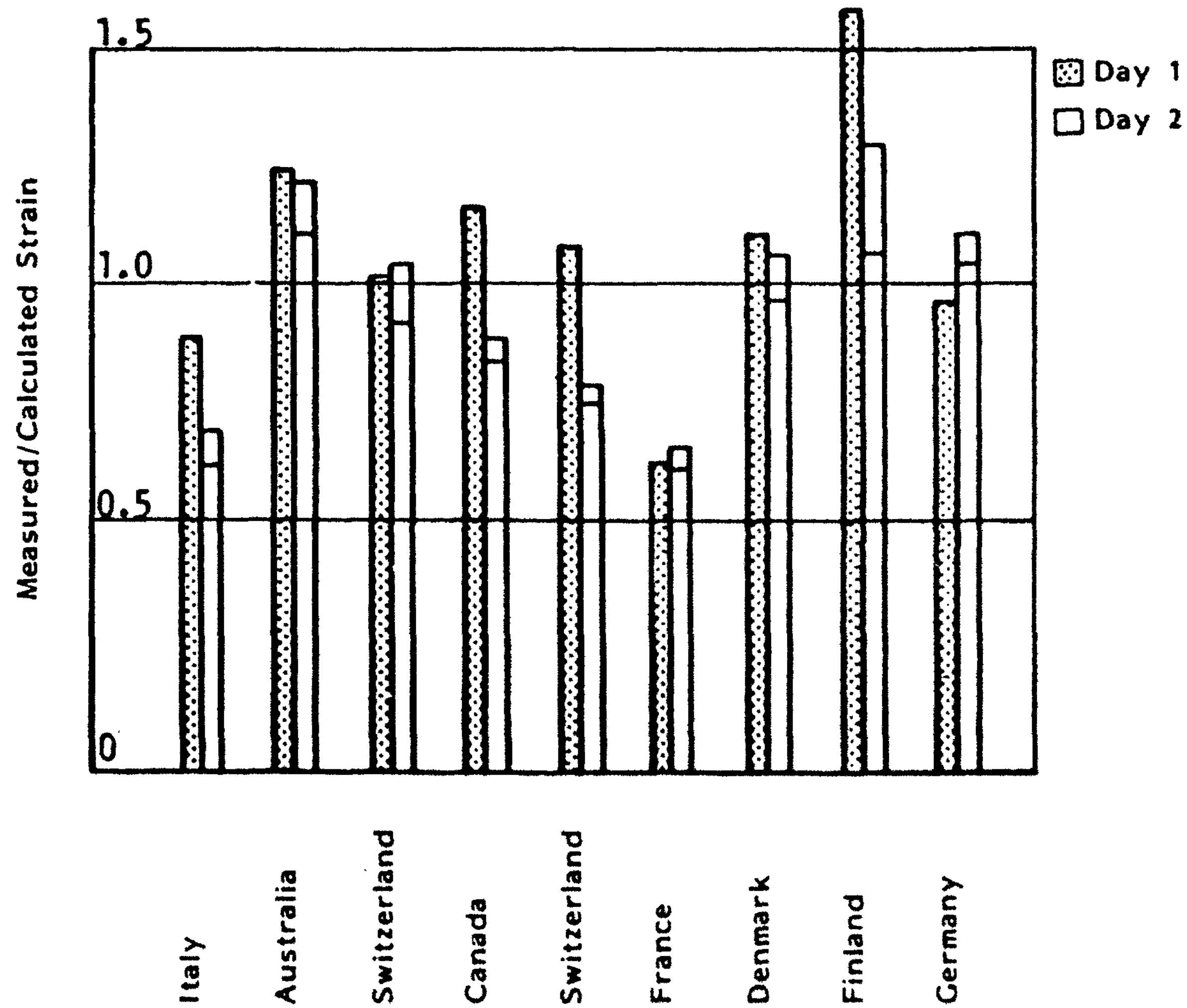


Figure 13. Ratio of Measured to Calculated Strain from FWD Testing—Nardò Test Facility [35]

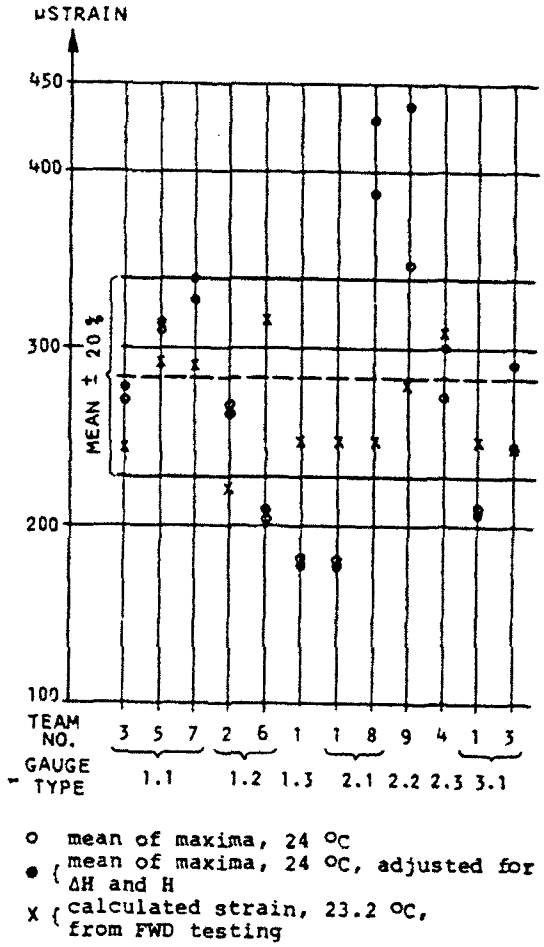


Figure 14. Comparison of Measured and Calculated Strains Adjusted for AC Temperature, AC Thickness, and Gauge Location—Nardò Test Facility [35]

for each team and gauge combination are compared to this range: strain calculated based on FWD moduli, mean of measured strain maximums, and mean of measured strain adjusted for layer thickness and gauge position. Most of the strains fall within the 20 percent range. Given the number of groups and techniques, the agreement was "astonishingly good." [35]

Dohmen and Molenaar [37] provided a review of three full scale pavement tests conducted by Dutch pavement engineers. All three tests showed reasonable agreement between measured and calculated strains. The first test was performed on test pavements at the Delft University test facilities. These pavements were subjected to 1,000,000 repeated plate loads. Before each application of 100,000 loads, strains generated by the load of a FWD were analyzed at a point 0.3 inches above the bottom of the AC layer. For the first series of tests, the thickness of the AC surface was 9.4 inches. The AC layer thickness was reduced by milling before each subsequent application of loads. The AC thickness for the second and third test series was 7.1 inches and 4.7 inches respectively. The agreement between measured and calculated strains for each series was extraordinary (see Table 7).

Table 7. Comparison of Measured and Calculated Strains —
Delft University Test Facility (after Dohmen and Molenaar [37])

Surface	Microstrain		Ratio
Thickness	Measured	Calculated	Measured/Calculated
9.4 in.	50	50	1.00
7.1 in.	79	78	1.01
4.7 in.	191	190	1.01

Strains calculated using BISAR.

The second test was conducted at the Laboratoire Central des Ponts et Chaussées (LCPC) facility in Nantes, France during the First OECD Road Common Experiment (FORCE). Once again, the measured and calculated strains (using BISAR) at the bottom of the AC layer under a FWD load were compared. The Dutch team conducted testing in two sections of the test pavement. Section 01 had a 4.8 inch (123 mm) AC surface and section 02 had a 5.5 inch (139 mm) AC surface. Figures 15 and 16 show the results for sections 01 and 02 respectively. Dohmen and Molenaar [37] proposed that the scatter in the data for both sections was caused by variability in the alignment of the FWD over the strain gauges. For Section 01, Dohmen and Molenaar [37] suspect that difficulty in backcalculating the layer moduli and possible cracking at the bottom of the AC layer also contributed to the disagreement.

The third study was performed at the Road and Railroad Lab (RRRL) of the Delft University of Technology. In this analysis, the strains at the bottom of the AC layer were measured in both the longitudinal and transverse directions. Comparisons of these measured and calculated strains due to a FWD load are shown in Figures 17 and 18. The variation in the measured strains is attributed to the gauge installation procedure and the uncertainty of FWD placement over the gauges. [37] The relationship between transverse and longitudinal strains observed by Dohmen and Molenaar [37] was opposite of that observed by Dempwolff and Sommer. [28] In their study (Dohmen and Molenaar [37]), the transverse strains were smaller than longitudinal strains for which no explanation was offered. The difference seen between the two tests (FWD and truck tire) could be attributed to the source of load and its potential effect based on placement over the exact gauge location. By examining the response of only one gauge in one of the pavement sections, Dohmen and Molenaar [37] have shown good agreement (see Figure 19).

Following the FWD testing, further testing was performed on the same test section using LINTRACK. LINTRACK is the linear ALD of the Delft University. Dohmen and Molenaar [37] compared both longitudinal and transverse strains at the bottom of the AC layer as calculated by BISAR and those measured under dual tires and super singles. They did find that the transverse strain under the center of the load was less than the longitudinal strain, as seen with a FWD load. [37] The difference was approximately 15-20 microstrains under the super singles and 30-40 microstrains in the

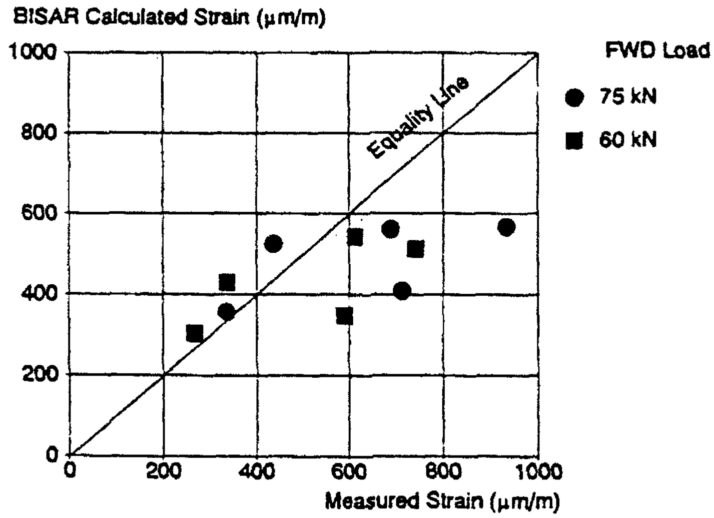


Figure 15. Comparison of Measured and Calculated Strains Due to a FWD Load—Section 01, FORCE Project [37]

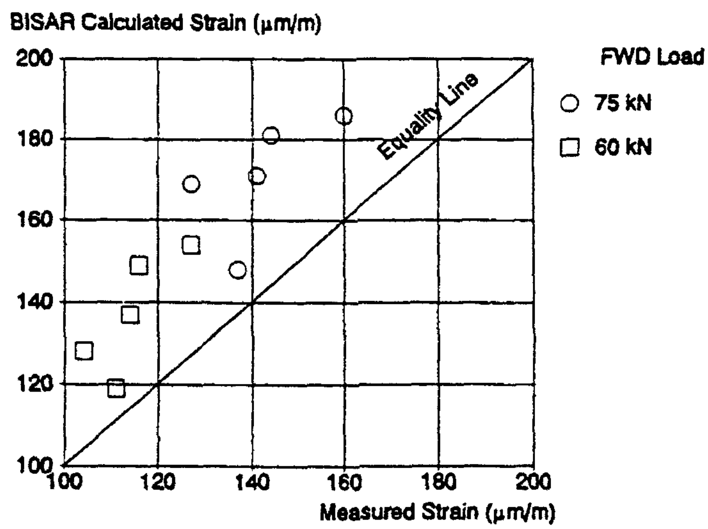


Figure 16. Comparison of Measured and Calculated Strains Due to a FWD Load—Section 02, FORCE Project [37]

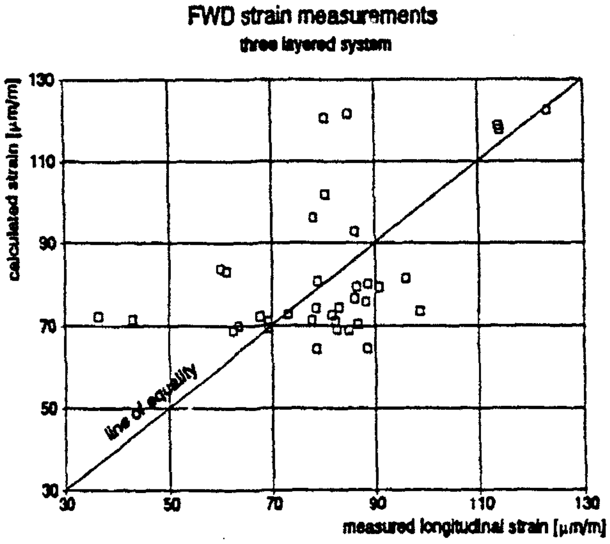


Figure 17. Comparison of Measured and Calculated Longitudinal Strains Due to a FWD Load—RRRL, Delft University of Technology [37]

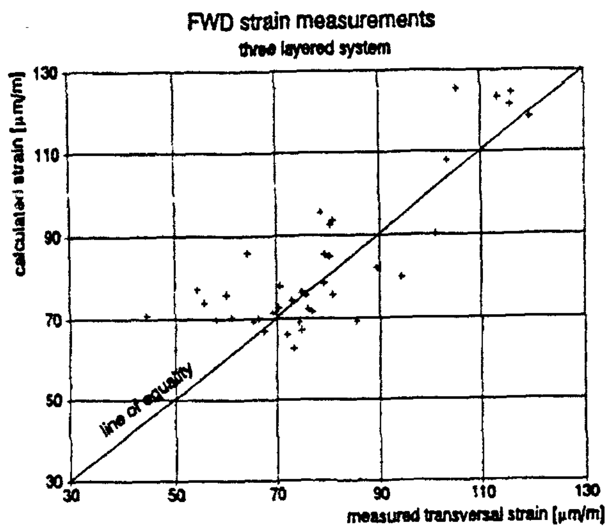


Figure 18. Comparison of Measured and Calculated Transverse Strains Due to a FWD Load—RRRL, Delft University of Technology [37]

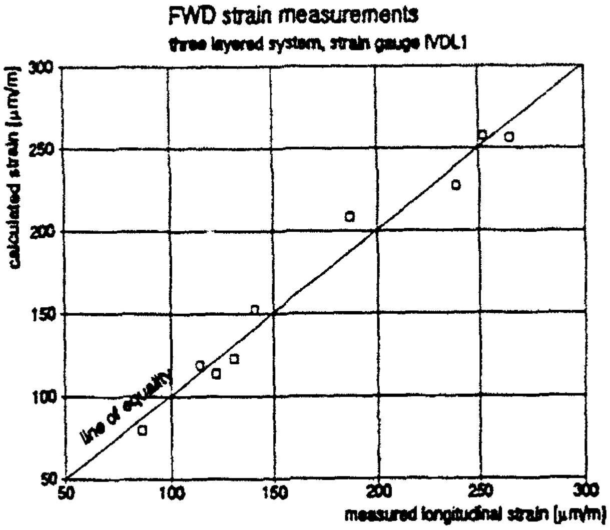


Figure 19. Comparison of Measured and Calculated Longitudinal Strains Due to a FWD Load for Gauge IVDL1—RRRL, Delft University of Technology [37]

dual wheel configuration. Dohmen and Molenaar [37] suspect that the difference between the actual and modeled contact pressure distribution could possibly have affected this difference.

One of the more recent instrumented flexible pavement studies was conducted by Sebaaly et al. [39] in 1989. One of the three main objectives of the study was to compare measured strains to calculated strains generated by mechanistic models. The test pavement consisted of two sections. The thick section had a 10 inch AC layer and the thin section had a 6 inch AC layer. The test vehicle was a single drive axle tractor pulling a tandem axle semi-trailer. One unique aspect of the testing program was a comparison of the performance of four different types of strain gauges as listed below.

1) Dynatest H - gauge,
2) Kyowa H - gauge,
3) Alberta Research Council (ARC) gauge, and
4) Core gauge.

The first three gauge types were installed during construction (after construction of the base course but before paving operations). The core gauges were retrofitted after construction. This provided the ability to compare the performance of gauges installed during construction to those installed in pavement cores. The results of this comparison would help address the uncertainties in instrumenting in-service pavements. The results from both sections at two loads are shown in Figures 20-23 which contain two sets of data points. The data points forming the band represent the upper and lower limit for the calculated strain based on a known deviation in AC layer thickness of ± 0.5 inch. The second set of points represent the mean and ± one standard deviation of the measured strain responses. For the thin section, the difference between measured and calculated response is small for all gauges except the ARC gauge. The thick section shows more variability but good agreement is evident for some of the gauges. The fact that the measured strains are greater than calculated at some stations and less than calculated at

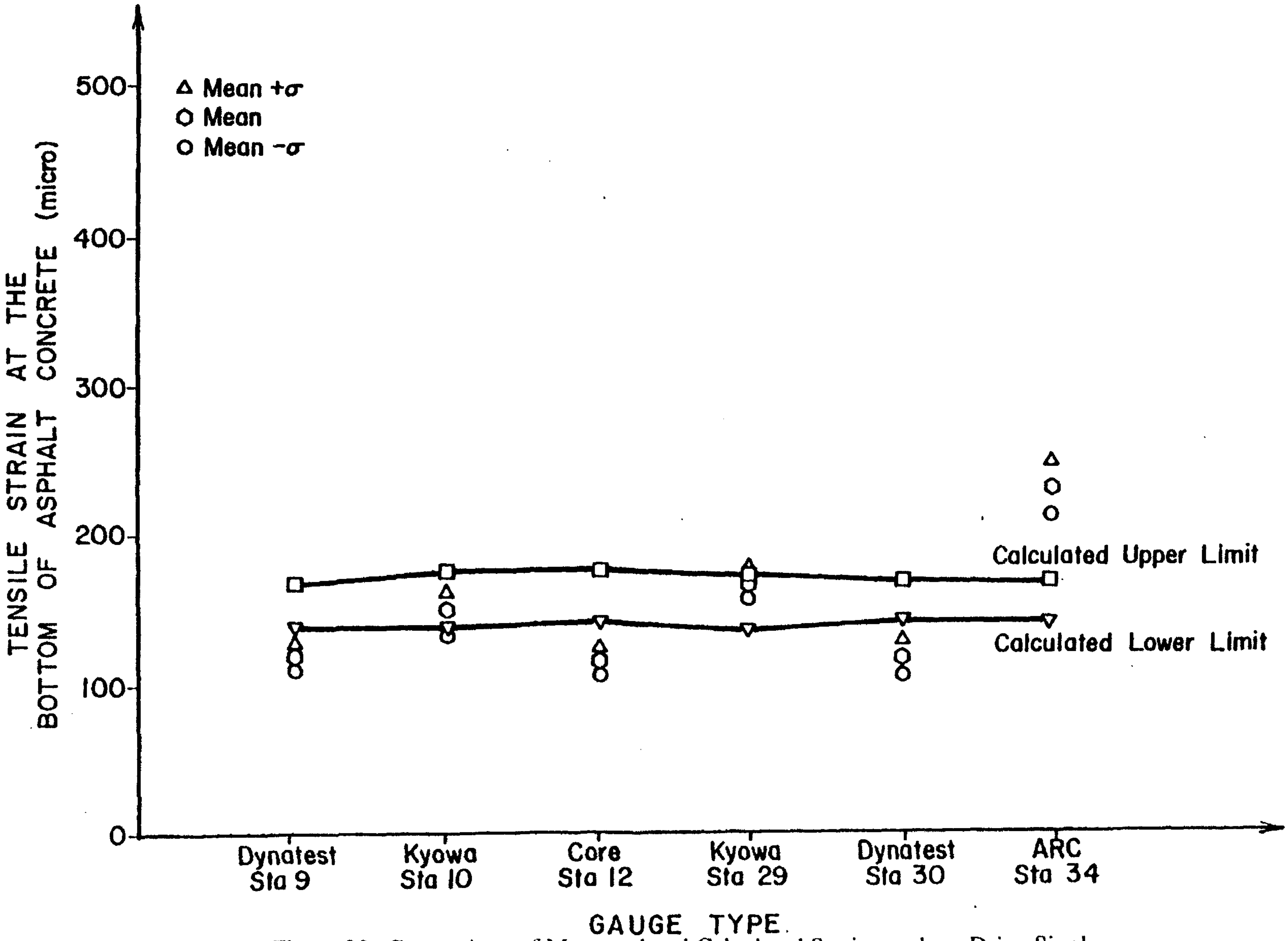


Figure 20. Comparison of Measured and Calculated Strains under a Drive Single Axle Load of 12,000 pounds—Thin Section [39]

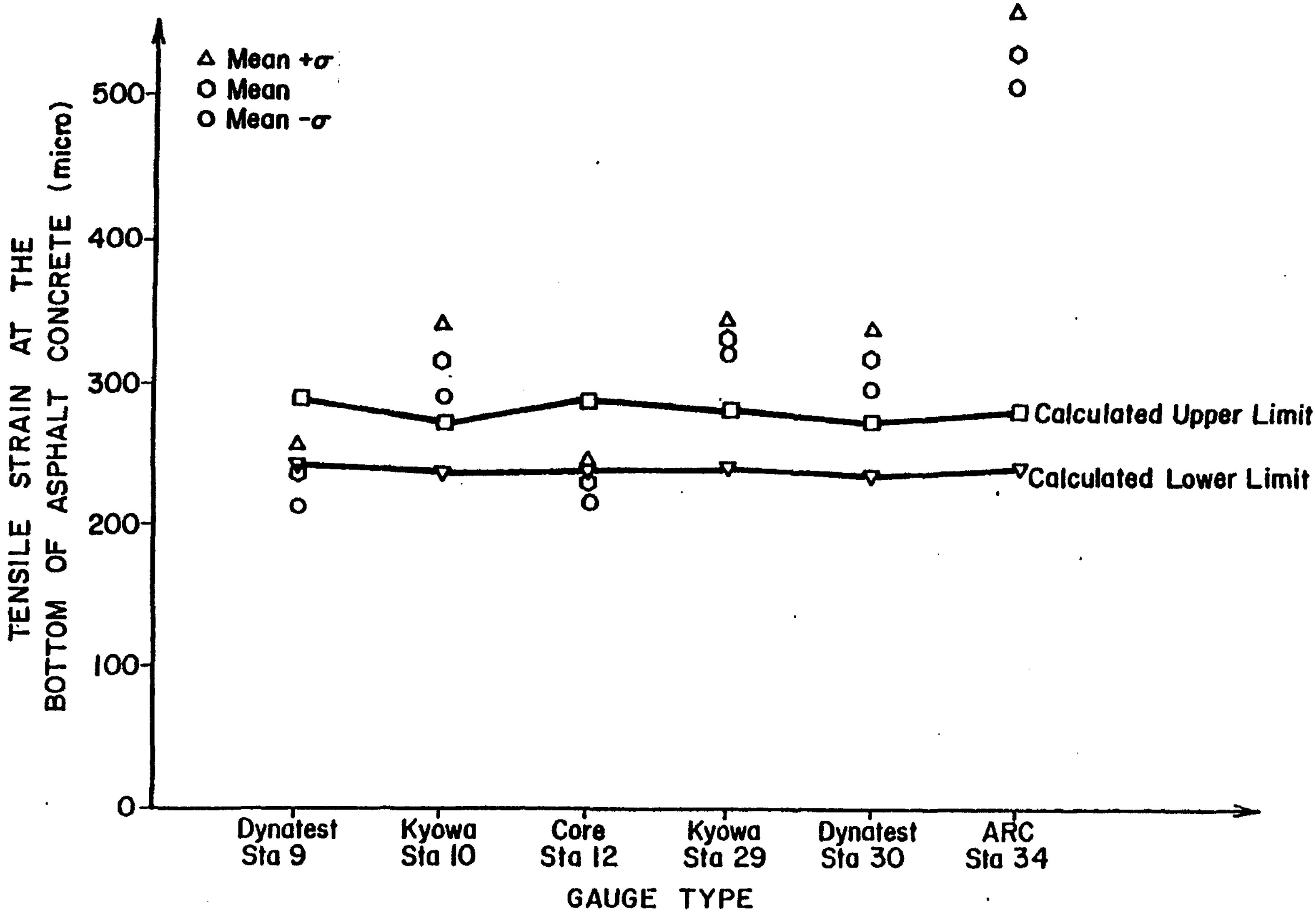


Figure 21. Comparison of Measured and Calculated Strains under a Drive Single Axle Load of 20,000 pounds—Thin Section [39]

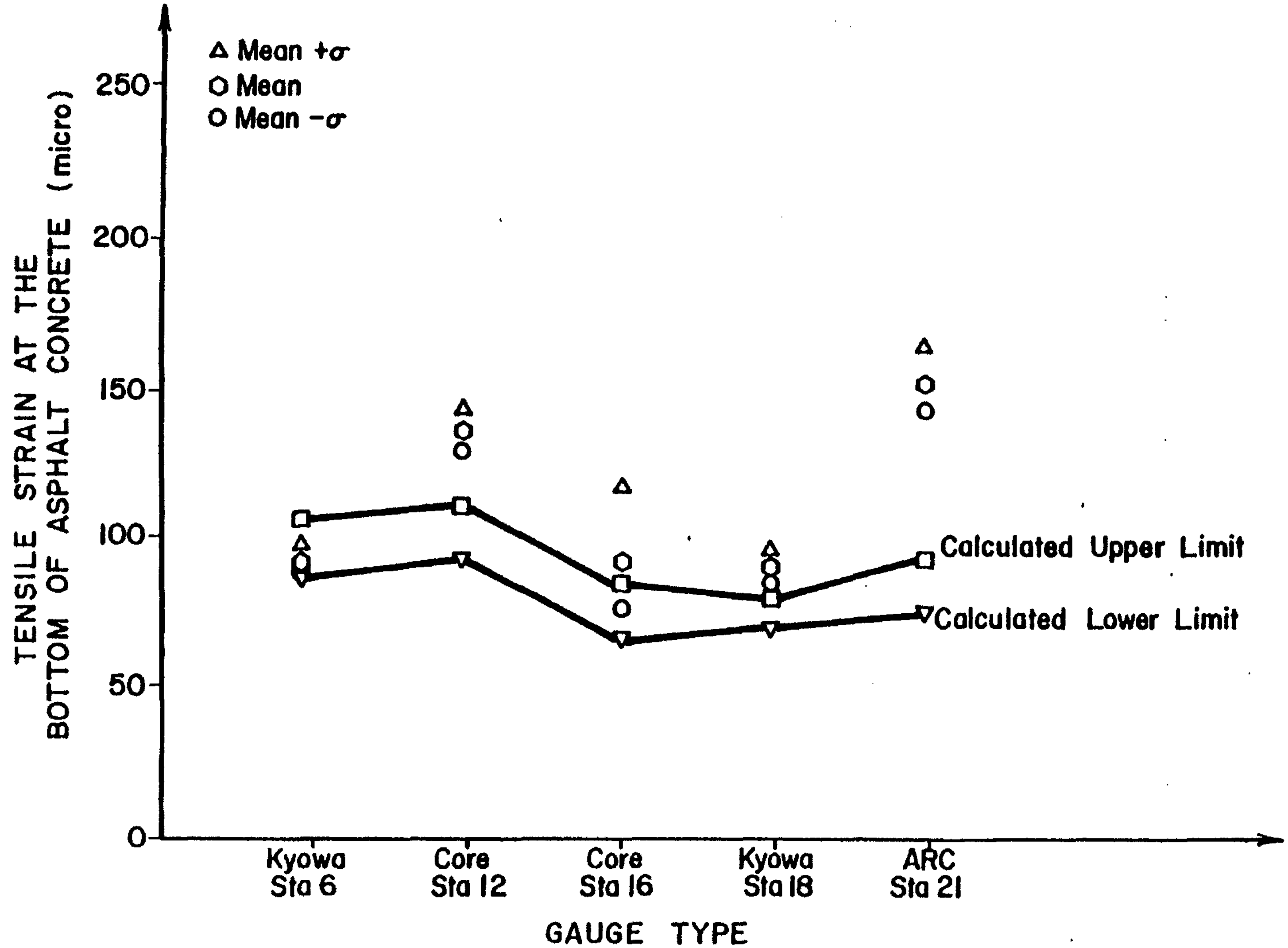


Figure 22. Comparison of Measured and Calculated Strains under a Drive Single Axle Load of 12,000 pounds—Thick Section [39]

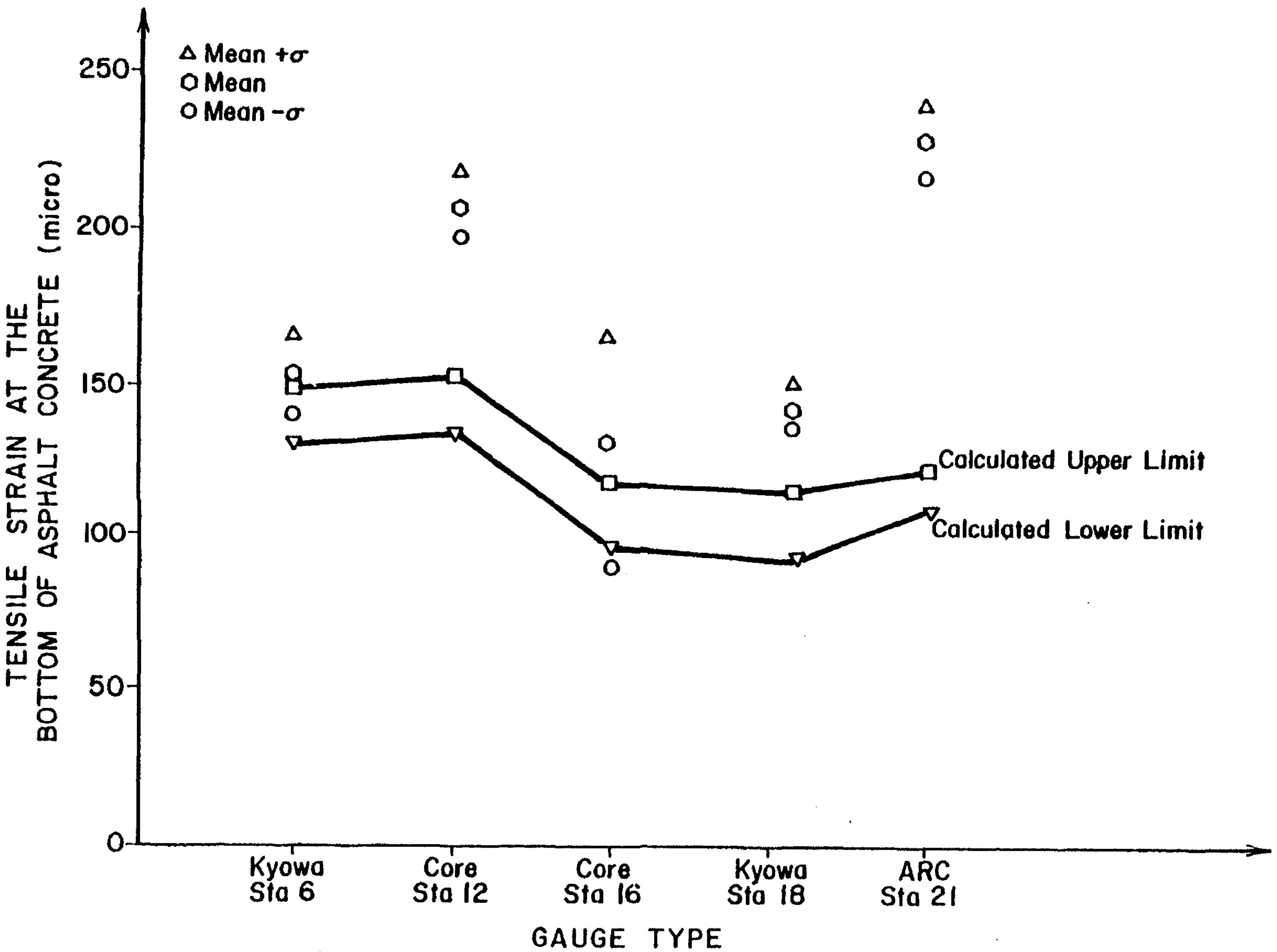


Figure 23. Comparison of Measured and Calculated Strains under a Drive Single Axle Load of 20,000 pounds—Thick Section [39]

other stations is attributed to the dynamic load profile. [39] It is interesting to note that the core gauge performed as well as, if not better than, the other gauge types.

At about the same time Sebaaly et al. [39] were conducting their work in the U.S., Lenngren [24] was comparing measured to calculated strains at the instrumented pavement test section at The Road and Traffic Laboratory in Finland. The test section contained two pavement structures. The thin structure had a 3.1 inch AC layer on top of a base and subbase totaling 24.4 inches. The 5.9 inch AC layer of the thick structure was above a base and subbase of 21.7 inches. The base and subbase of both structures were composed of sand and gravel; the only difference being in maximum aggregate size (1 in. in the base, 2 in. in the subbase). The instrumentation in this section consisted of strain gauges glued to 6 inch diameter cores retrofitted to the pavement. Horizontal tensile strains at the bottom of the AC layer were measured under the load generated by a KUAB 50 FWD. Three load levels were used: 2000, 5000, and 11,000 pounds. Layer moduli were backcalculated from the FWD deflection data using CLEVERCALC (a metric modification of EVERCALC). A comparison of the strains measured under the FWD load and calculated by CLEVERCALC for both structures is shown in Tables 8 and 9. The backcalculated layer moduli were used as input to BISAR to provide a comparison of the calculated strain at the bottom of the AC layer. The strain differences calculated by the two computer programs were negligible (1 microstrain). The majority of the measured strains were within ± 10 percent of calculated. The maximum difference was 20 percent.

This review of previous testing on instrumented flexible pavements demonstrated that a reasonable comparison between measured and calculated strains can be achieved under a wide variety of experimental conditions as listed below.

1. Pavement Loading

    a) Magnitude of Load

Table 8. Comparison of Measured and Calculated Strains at the Bottom of the AC Layer — 3.1 inch Section: Road and Traffic Laboratory, Finland (after Lenngren [24])

Time	Load (pounds)	Microstrains		% Difference
		Measured	Calculated	
pm	11723	283	295	-4%
pm	11723	283	284	0%
pm	5715	159	174	-9%
pm	5715	159	167	-5%
pm	5715	158	176	-11%
pm	5715	158	167	-6%
pm	2880	84.8	95	-12%
pm	2880	84.8	87	-3%
pm	2880	84.2	82	3%
pm	2880	84.2	81	4%

Absolute Average 6%
Arithmetic Average -4%

Strains calculated using CLEVERCALC.

Table 9. Comparison of Measured and Calculated Strains at the Bottom of the AC Layer—5.9 inch Section: Road and Traffic Laboratory, Finland (after Lenngren [24])

Time	Load (pounds)	Microstrains		% Difference
		Measured	Calculated	
pm	11273	185	189	-2%
pm	11273	185	178	4%
pm	11318	183	186	-2%
pm	11318	183	182	1%
pm	5715	95.9	103	-7%
pm	5715	95.9	104	-8%
pm	2880	48	57	-19%
pm	2880	48	51	-6%
pm	2880	48.5	58	-20%
pm	2880	48.5	56	-15%

Absolute Average 8%
Arithmetic Average -5%

Strains calculated using CLEVERCALC.

b) Source of Load

i) plate loading
ii) truck axle
iii) accelerated loading device
iv) Falling Weight Deflectometer

2. Pavement Structures

3. Theoretical Comparison

4. Strain measurement techniques (gauge type)

The range of these conditions organized by source of pavement load is summarized in Table 10. It appears that a wide range of testing conditions has been evaluated.

Another important observation is that generally speaking, a range of 20 percent is regarded as a reasonable expectation when comparing measured to calculated strains.

One important question was raised and remains unanswered. Why are longitudinal and transverse strains at a particular evaluation location unequal? Additionally, in some cases the longitudinal strains are larger; in others the transverse strains are larger. It appears possible that for testing under wheel loads, this difference could be attributed to variations in contact pressure distributions based on varying tire loads. For FWD testing, it could be explained by not having the load plate centered over the strain gauge location.

7.3 Comparison of Various Strain Measurement Techniques (Gauges)

Sebaaly et al. [27, 39] have conducted an in-depth literature review and field performance testing of various strain gauges. In their literature review (Sebaaly et al. [27]), strain gauges used in bonded layers fall into four categories:

1. H-gauges and strip gauges,

2. Foil gauges glued to or embedded in carrier blocks prepared in the laboratory,

3. Foil gauges glued to cores extracted from the pavement section, and

4. Strain coils.

Table 10. Range of Experimental Conditions From Various Instrumented Flexible Pavement Tests

Source of Load [Reference(s)]	Load Magnitude (pounds)	Pavement Structure (inches)	Gauge Type	Theoretical Comparison
Plate Loading from a Hydraulic Actuator [33]	2250 to 9000	AC: 4.5 to 9.8 BS: None	Foil gauges and mastic carriers	BISAR
FWD [24, 37]	2813 to 16,875	AC: 3.1 to 9.4 BS: 0 to 11.0	Core, TML, Dynatest	BISAR, CLEVERCALC
Single Wheel Loads (vehicular) [4, 11, 26, 30, 32, 35,]	450 to 9000 per wheel	AC: 1.0 to 11.0 BS: 0 to 33.9 CTB, ATB, CTS SB: 0 to 3.9 (LTB)	SR4, SR4 in carrier blocks, gauges attached to sand asphalt, electric resistance, UK strain meters	Boussinesq, Burmister 2-layer, Jones' Tables, Chevron, BISAR
Dual Wheel Loads (vehicular) [4, 31, 35]	5000 to 15,400 per wheel	AC: 2.0 to 10.0 BS: 4.0 to 12.0 CTB, ATB SB: 0 to 6.7	SR4, SR4 in carrier blocks, electric resistance molded by epoxy and polyester resin, H-gauges, gauges in carrier blocks, core, Kyowa, ARC	Boussinesq, Burmister, MET, BISAR, PENMOD
Single Wheel ALF [28, 29, 37]	880 to 11,250 per wheel	AC: 5.5 to 8.7 Open, Dense BS: 0 to 33.9	Gauges in carrier blocks	Jones' Tables, BISTRO, BISAR
Dual Wheel ALF [34, 36, 37, 38]	9400 to 19,000 per set of duals	AC: 2.0 to 7.0 BS: 0 to 17.7	H-gauges glued to aluminum or plexiglass backing, TML	ALIZE III, ELSYM5, BISAR

The H-gauge is made of a strip of material upon which a strain gauge is attached. Metallic bars are attached to both ends of the strip to serve as anchors. These gauges are called H-gauges because the resulting shape of the assembly resembles the letter "H". As the pavement strains under a load, the anchor moves with the pavement causing the strip to elongate and hence a strain measurement. For the gauge to experience (and measure) the same strain as the pavement the stiffness of the strip material must be approximately equal to or slightly less than that of the AC layer. Additionally, the anchors must remain firm so as not to introduce artificial elongation. Many models and varieties of these gauges have been built using different materials and slightly differing designs to attempt to overcome these challenges. [27]

The use of carrier blocks prepared in a lab has also been common. In this application, a foil type gauge is either glued to a lab specimen, glued between two pieces of a lab specimen or embedded in a lab specimen. The theory behind this application is that the lab specimen will melt somewhat when the hot mix is placed around it. As a result, the carrier block will become a contiguous part of the AC layer. [27]

Mounting foil gauges to pavement cores is very similar to that of carrier blocks. The obvious difference being that the strain gauge "carrier" is actual in-situ material versus laboratory prepared material. The major concern with this technique is the epoxy used to bond the core back to the pavement structure. The stiffness of the epoxy should match that of the AC as closely as possible. Epoxy that is too soft could cause the bond to fail. Epoxy that is too stiff could cause cracking around the core. [27]

Strain coils work on an electromagnetic output and are usually installed in carrier blocks. Their output can be affected by metallic wheels and vehicular ignition systems. [27] Their use is virtually nonexistent in the literature. See Ref. [27] for a more detailed discussion of the characteristics of all these gauge types.

As previously mentioned, Sebaaly et al. [39] conducted a field performance evaluation of a selected group of strain gauges (Table 11) and established four performance related criteria. The four criteria and their definitions are as follows.

1. Survivability — "...the number of gauges that remain operational after construction and testing relative to the number of gauges that were initially installed." [39]

2. Repeatability — "...a measure of dispersion of measuring results obtained from a specific gauge for specific test conditions." [39]

3. Effect of Test Variables — "...the sensitivity of each type of gauge to various combinations of load, speed, tire pressure, and axle configuration." [39]

4. Uncertainty — "...the difference between the measured response and the theoretically calculated values." [39]

This discussion will only highlight the performance of the gauges installed to measure one of the primary pavement responses for mechanistic-design -- strain at the bottom of the AC layer.

The survivability data for the gauges installed in the thin and thick sections is contained in Tables 12 and 13, respectively. Survivability varied across gauge types and pavement sections. The two ARC gauges were the only gauges with perfect survivability in both sections. The core gauges (transverse and longitudinal) had the next best survival rate at 60 percent after installation and testing. All the failures occurred in the thick section after testing. All four of the Dynatest gauges survived construction but only half survived testing. Like the core gauges, all the failures were in the thick section. The Kyowa gauges demonstrated the least favorable survivability with just over 60 percent of the gauges surviving construction and only 50 percent remaining operational after testing. These results are summarized in Table 14. It is noteworthy that the worst overall survivability rate by section was found in the thick section. Sebaaly et al. [39] did not make this observation and as such provide no explanation. Also, the original authors did not address the pavement condition at the conclusion of testing. Therefore, it is unknown

Table 11. Strain Gauges Evaluated During Field Performance Testing (after Sebaaly [39])

Gauge Type	**Number of Gauges/Section**	**Orientation**	**Location**
Dynatest (H)	2/thin and thick	Longitudinal	Bottom of AC Layer
Kyowa (H)	4/thin and thick	Longitudinal	Bottom of AC Layer
Asphalt Carrier Block (ARC)	1/thin and thick	Longitudinal	Bottom of AC Layer
Core	4 thick	Longitudinal	Bottom of AC Layer
Core	1 thin	Transverse	Bottom of AC Layer

Table 12. Survivability of Gauges Installed in the Thin Section (after Sebaaly [39])

Gauge Type	Number Installed	After Construction/Installation		After Testing	
		Number Surviving	Percent Operational	Number Surviving	Percent Operational
Dynatest	2	2	100%	2	100%
Kyowa	4	3	75%	2	50%
ARC	1	1	100%	1	100%
Core (Transverse)	1	1	100%	1	100%
Totals	8	7	88%	6	75%

Table 13. Survivability of Gauges Installed in the Thick Section (after Sebaaly [39])

Gauge Type	Number Installed	After Construction/Installation		After Testing	
		Number Surviving	Percent Operational	Number Surviving	Percent Operational
Dynatest	2	2	100%	0	0%
Kyowa	4	2	50%	2	50%
ARC	1	1	100%	1	100%
Core (Longitudinal)	4	2	50%	2	50%
Totals	11	7	64%	5	45%

Table 14. Survivability of Gauges—Both Pavement Sections (after Sebaaly [39])

Gauge Type	Number Installed	After Construction/Installation		After Testing	
		Number Surviving	Percent Operational	Number Surviving	Percent Operational
Dynatest	4	4	100%	2	50%
Kyowa	8	5	63%	4	50%
ARC	2	2	100%	2	100%
Core	5	3	60%	3	60%
Totals	19	14	74%	11	58%

if excessive pavement deterioration contributed to any of the gauge failures. Given that each section received approximately 125 truck passes with a maximum axle load of 20,820 pounds, this is unlikely.

In the area of repeatability, Sebaaly et al. [39] performed two sets of analyses. First, an evaluation was made "...of the means, standard deviations, and coefficients of variation for the four replicate measurements for each combination of the test variables." [39] To "...increase the number of observations and reduce the effect of potential random error in the collected data" the data was pooled by test variable combinations. The standard deviation of the measured strains in each pooling was also evaluated. From their data analysis, Sebaaly et al. [39] concluded that the repeatability of all the gauges was "...very good even under the conditions that created relatively high standard deviations."

In studying the effects of the test variables (axle load, tire pressure, and truck speed) on gauge performance Sebaaly et al. [39] drew the following conclusions.

1. "[T]he effect of tire pressure on strain at the bottom of the asphalt concrete layer is insignificant compared to the effects of axle load and truck speed for all types of strain gauges." [39]

2. "[T]he effect of increasing load level from the intermediate to the fully loaded level on the measured strains was consistent among all types of gauges under both the single and tandem-axle configurations. However, the effect of increasing the load level from empty to the intermediate level on the measured strain was less consistent." [39]

3. "[I]t [was] impossible to correlate the speed effect to specific gauge types." [39]

The analysis of potential uncertainty in gauge measurements has already been presented (see Figures 20-23).

The final form of analysis conducted by Sebaaly et al. [39] was a regression analysis using the response from each gauge type as the dependent variable and the overall mean of all gauge types as the independent variable. [39] The ARC gauges were excluded from this analysis because of the high uncertainty in their measured responses. The results of the regression analysis are contained in Table 15. The performance of the

Table 15. Statistical Summary of the Regression Analysis of All Measured Strain Responses (after Sebaaly et al. [39])

Dependent Variable	Intercept (a)	Slope (b)	Sample Size	R-squared %	Std. Error of Est.	Mean	Minimum	Maximum
Dynatest	-5.58	1.017	399	98.70	13.32	139.2	2	622
Kyowa	-3.18	1.108	480	97.94	17.33	141.3	5	632
Core	12.59	0.768	478	93.15	22.31	112.2	11	462

Independent Variable: Average value of all the gauges.

Dynatest and Kyowa gauges is essentially equal. Compared to the H-type gauges (Dynatest and Kyowa) the core gauges performed less consistently. However, one must realize that the installation procedures and strain measurement concepts between the two gauge types are very different. [39] Sebaaly et al. [39] present two possible explanations for the difference in performance between the two gauge types.

1. Use of epoxy to glue the gauges to the cores.
2. The ability of the core to become an integral part of the pavement section.

Another important consideration is the type of application in which the two gauge types are used. Core gauges can be retrofitted to new and existing pavements. H-type gauges must be installed before paving operations. Because of their exclusive ability to be retrofitted to in-service pavements further study should be conducted to establish an effective calibration procedure to account for the effect of the epoxy used to mount the gauges to the pavement core. [39]

CHAPTER 3

EVALUATION OF THE PACCAR PAVEMENT STRUCTURE

1. INTRODUCTION

The purpose of this chapter is to provide a brief description of the test section at the PACCAR Technical Center and make a general characterization of the material properties of the pavement layers based on deflection data from FWD testing. Additionally, evidence that suggests that a saturated soil condition triggers the stiff layer algorithm in EVERCALC 3.3 will be provided. An appropriate layer modulus for this "stiff layer" will also be discussed.

The test section was built to meet the specific objectives outlined in the research proposal [1] and as stated in Chapter 1. The test pavement was also constructed using routine materials and construction practices and its size accommodates the operation of a Class 8 truck.

2. DESCRIPTION OF THE PACCAR TEST SECTION

The test pavement is located at the PACCAR Technical Center at Mount Vernon, Washington (about 60 miles north of Seattle). It is a flexible pavement surfaced with 5.4 inches (mean value) (see Table 16) of dense graded AC (WSDOT Class B) over a 13.0 inch crushed stone base. The subgrade is a sandy clay. A cross section of the pavement structure is shown in Figure 24. The water table was measured at a depth of 66 inches during installation of the instrumentation.

Fifteen AC core samples were taken from the section for installation of the instrumentation. These cores were used to conduct various tests of the materials. The coring and materials testing were conducted by WSDOT. The results are contained in Tables 16 and 17. Table 16 shows that based on the 15 samples taken, the AC is

Table 16. Results of Thickness and Density Evaluation of AC Surfacing—PACCAR Test Section

Core Number	AC Thickness (in.)	Bulk Density	Rice Density	Percent Voids
1	5.16	2.300	2.503*	8.1
2	5.16	2.326	2.503*	7.1
3	5.16	2.387	2.503*	4.6
4	5.28	2.368	2.503*	5.4
5	5.16	2.347	2.503*	6.2
6	5.40	2.289	2.505	8.6
7	5.16	2.349	2.502	6.1
8	5.40	2.369	2.503*	5.4
9	5.28	2.326	2.503*	7.1
10	5.76	2.297	2.503*	8.2
11	5.52	2.315	2.503*	7.5
12	5.64	2.301	2.503*	8.1
13	5.76	2.285	2.503*	8.7
14	5.64	2.278	2.503*	9.0
15	5.52	2.313	2.503*	7.6

Mean	5.40	2.323	N/A	7.2
Standard Deviation	0.23	0.034	N/A	1.4
Minimum	5.16	2.278	N/A	4.6
Maximum	5.76	2.387	N/A	9.0
Count	15	15	N/A	15

Notes:
Rice densities performed on cores 6 and 7 only.
* Average of Rice densities from cores 6 and 7 used to determine air voids.

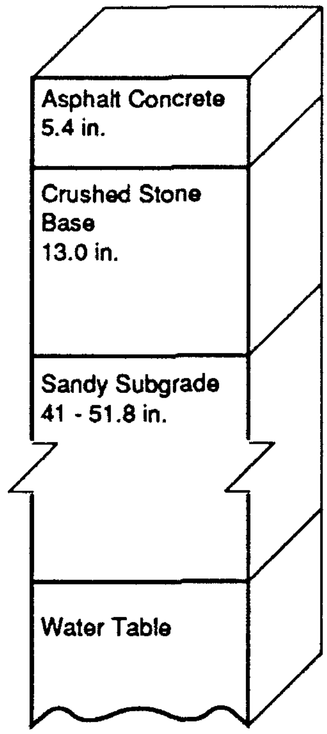


Figure 24. Cross Section of the PACCAR Test Section

relatively homogeneous and of a generally uniform thickness. Table 17 compares the gradation of axial Cores 1 through 5 to the gradation band for WSDOT Class B ACP. Percent passing data for WSDOT Class B ACP is illustrated in Figure 25. The PACCAR mix mostly falls within the Class B band except for the No. 200 sieve.

The instrumented section is approximately 14 feet wide and 40 feet long It is located along a section of the durability track at the Technical Center (see Figure 26). It is closed to vehicular traffic except during scheduled pavement testing. There is standing water virtually year round in the infield adjacent to the test section.

3. BACKCALCULATION OF LAYER MODULI

The first step in evaluating a test section is to establish the material properties for each of the layers in the pavement structure. As discussed previously, there are two basic methods: laboratory testing and field testing. For this test section, a combination of both methods was used. Laboratory testing to verify AC layer thickness and evaluate the asphalt concrete mixture was discussed above. Backcalculation of FWD deflection data was used to establish appropriate layer moduli.

3.1 PACCAR Test Section

During October 1991, the WSDOT Dynatest 8000 FWD was used to obtain deflection measurements at 61 separate locations (130 drops). One basin was deleted due to a faulty sensor reading at the 8 inch offset. The applied loads varied from 4,874 to 14,527 pounds. Sensor spacings for the FWD were set at 0, 8, 12, 24, 36, and 48 inches. During testing, the measured average mid-depth temperature of the AC layer was 68°F. By use of EVERCALC 3.3, the layer moduli were estimated for various conditions using the previously mentioned layer thicknesses (surface and base) and Poisson's ratios of 0.35 (AC) and 0.40 (base). The pavement structure was modeled as a four layer system by inclusion of the stiff layer option in EVERCALC.

Table 17. Results of Extraction and Gradation of Cores 1 through 5 - PACCAR Test Section

Sieve Size	Percent Passing					
	Core Number					WSDOT Class B
	1	2	3	4	5	
5/8	100	100	100	100	100	100
1/2	98	98	98	99	99	90-100
3/8	89	89	90	92	89	75-90
1/4	68	67	71	74	69	55-75
10	36	37	37	39	37	32-48
40	17	18	18	19	18	11-24
80	11	12	12	12	12	6-14
200	7.4	8.3	8.0	8.4	8.1	3-7
% Asphalt	5.4	5.1	5.1	5.5	5.0	

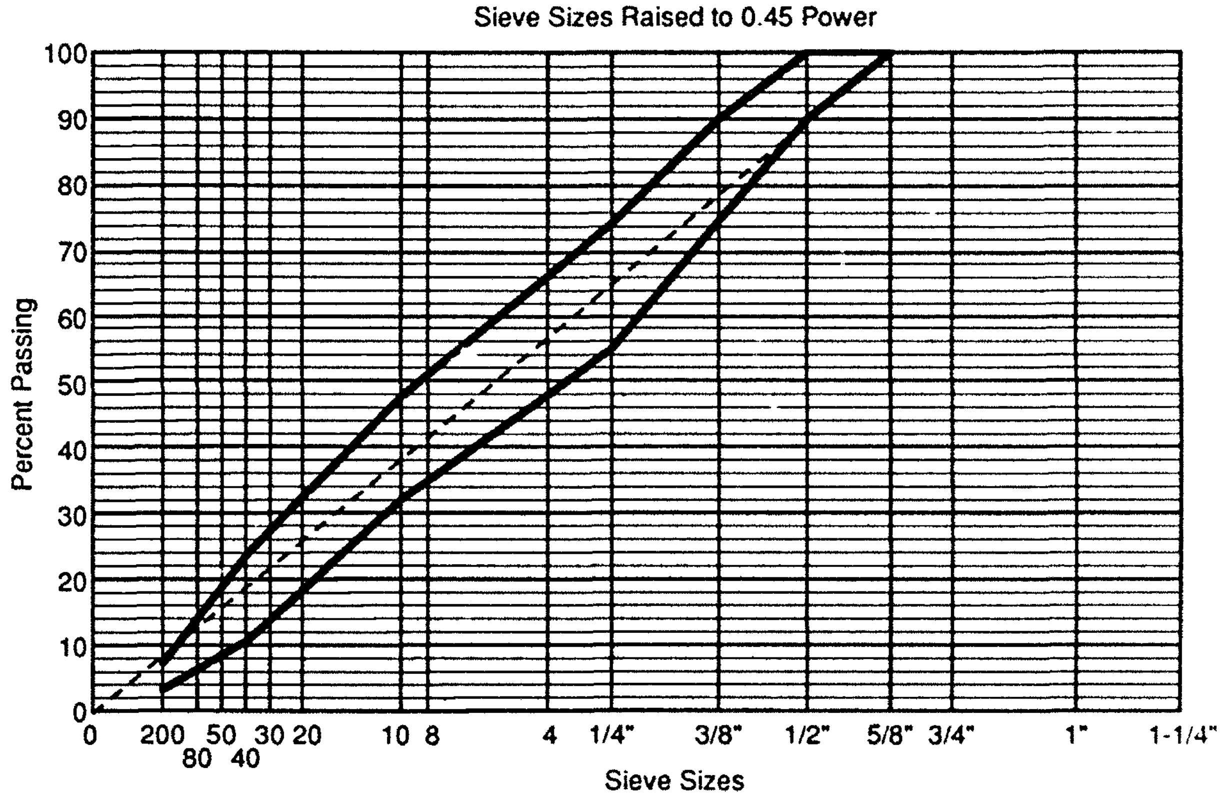


Figure 25. Maximum Density Curve (0.45 Power) for 5/8 in. Maximum Aggregate with the Gradation Band for WSDOT ACP Classes A and B [7]

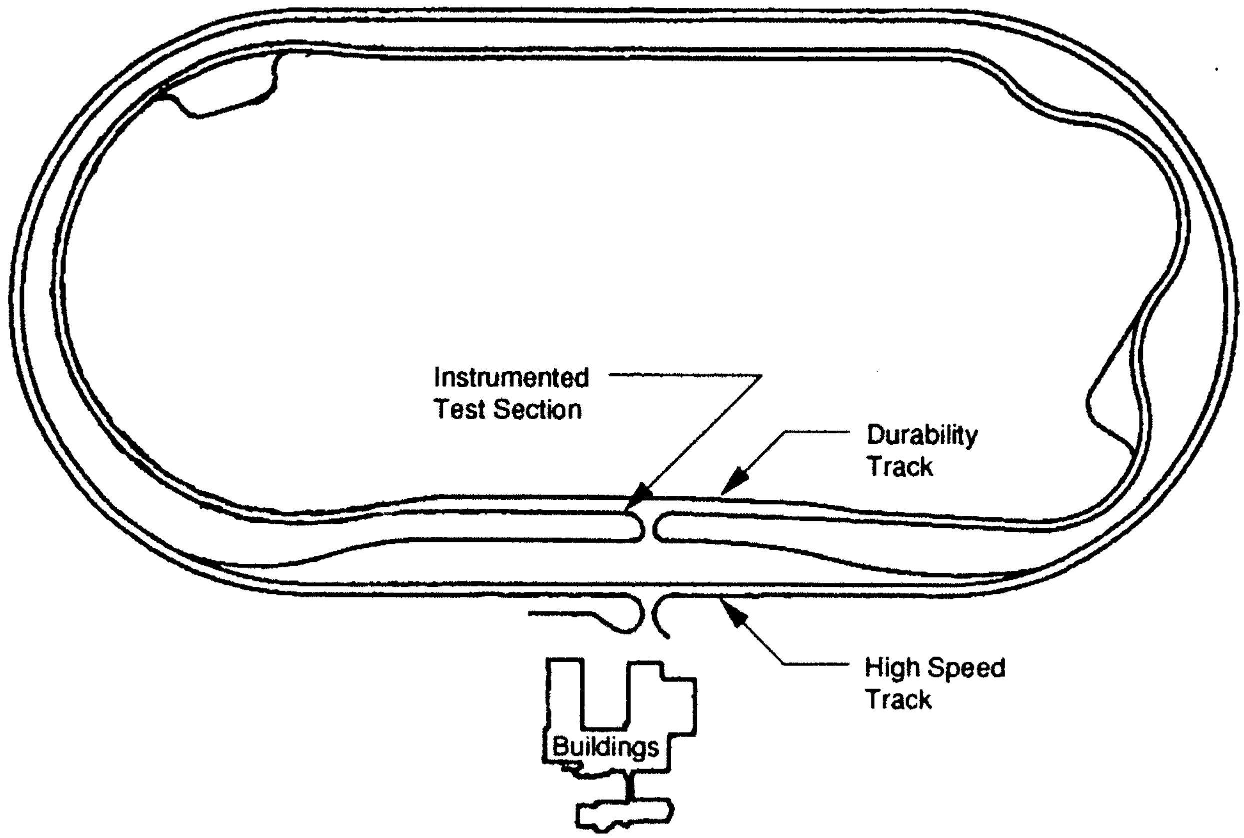


Figure 26. PACCAR Technical Center – Plan View

Initially, the stiff layer was fixed with a modulus of 1,000 ksi and the depth to stiff layer algorithm estimated the top of the stiff layer between 60 and 70 in. which was extremely close to the measured depth of water table (see Table 18). Further, there are no known rock or other major layer transitions within several feet of the surface at this site. Using the 1,000 ksi modulus for the stiff layer, only 31 of the 130 deflection basins resulted in an RMS error convergence of 2.5 percent or less (2.5 percent was used as an acceptable upper limit). Thus, it was decided to try various values for the stiff layer modulus ranging from a low of 10 ksi to a high of 1,000 ksi. The resulting layer moduli are shown in Table 19 and associated RMS statistics in Table 20.

Table 18. Calculated (EVERCALC 3.3) Depth to Stiff Layer Based on October 1991 FWD Testing—PACCAR Test Section

DEPTH TO STIFF LAYER	(inches)
Mean	64.9
Standard Deviation	2.9
Minimum	59.4
Maximum	70.2
Number of Drop Locations (n)	61

The results suggest that the stiff layer was "triggered" by the saturated conditions below the water table and, for this condition, a stiff layer modulus of about 40 ksi is more appropriate than the traditional value of 1,000 ksi. This observation is based on the RMS and AC modulus values. For example, the AC modulus of 563 ksi corresponds to an expected value of about 600 ksi based on previously conducted laboratory tests for WSDOT Class B mixes — a rather close agreement (see Figure 27 [42]). The base modulus of 15 ksi might be a bit low but the subgrade modulus of 10 ksi appears to be reasonable (based on soil type).

The effect of using various stiff layer stiffnesses can be illustrated by use of one of the critical pavement response parameters (horizontal tensile strain at the bottom of the AC) used in mechanistic-empirical pavement design (new or rehabilitation) discussed in

Table 19. Sensitivity of Layer Moduli as a Function of the Stiff Layer Modulus — PACCAR Test Section, October 1991 FWD Testing

PAVEMENT LAYERS	E_{stiff}						
	10 ksi	25 ksi	40 ksi	50 ksi	75 ksi	100 ksi	1000 ksi
Asphalt Concrete* (ksi)	884	828	563	476	405	368	284
Crushed Stone Base* (ksi)	2.5	4.2	15	20	27	30	42
Fine-grained Subgrade* (ksi)	1436	43	10	8.5	7	7	5.3
Total Runs with RMS% <=2.5*	22	113	120	118	80	77	31

*Calculated from runs with a RMS% <=2.5%.

Table 20. Sensitivity of RMS Values as a Function of the Stiff Layer Modulus — PACCAR Test Section, October 1991 FWD Testing

RMS (%)	E_{stiff}						
	10 ksi	25 ksi	40 ksi	50 ksi	75 ksi	100 ksi	1000 ksi
Mean*	3.0	1.4	1.3	1.7	2.3	2.6	3.8
Standard Deviation*	0.7	0.8	0.9	1.0	1.2	1.3	1.6
Minimum*	1.4	0.4	0.2	0.2	0.6	0.8	1.4
Maximum*	5.6	5.2	6.9	7.5	8.2	8.5	9.4
Total Runs with RMS% <=2.5*	22	113	120	118	80	77	31

*Calculated for 129 deflection basins.

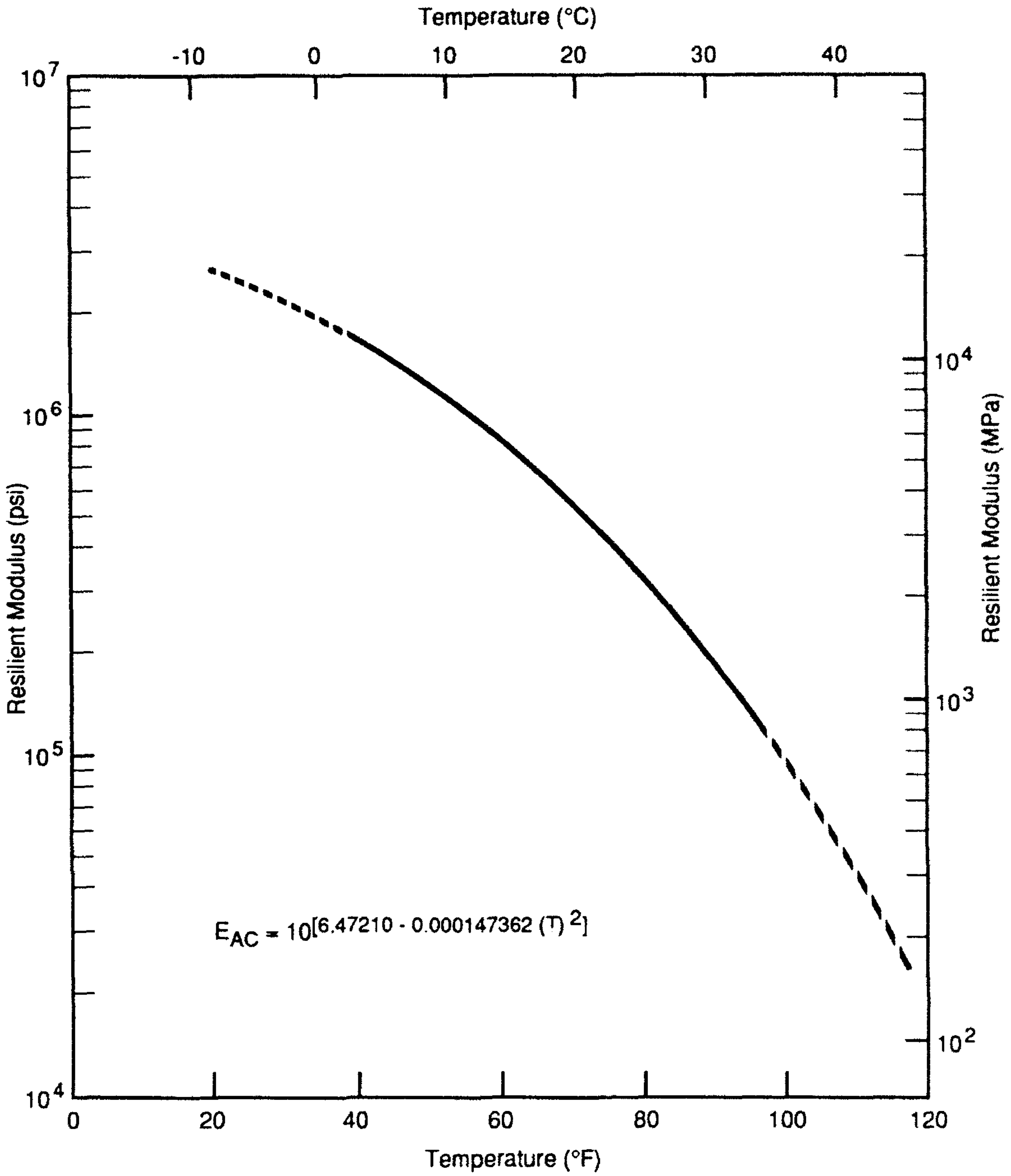


Figure 27. General Stiffness-Temperature Relationship for Class B (Dense Graded) Asphalt Concrete in Washington State [42]

Chapter 2, Section 3. Figure 28 shows the strain backcalculated from the October 1991 deflection data versus FWD load using all deflection basins that converged with a RMS error percentage at or below 2.5 percent at each of the three stiff layer conditions. Clearly, the estimated strain levels are significantly influenced by the stiff layer modulus condition.

Layer moduli backcalculated from the October 1991 FWD deflection data were plotted as a function of FWD load to examine the suitability of using layered elastic analysis to determine the layer moduli for the PACCAR section. The layer moduli were backcalculated from the 122 deflection basins that converged with a RMS error percentage at or below 2.5 percent. The stiff layer modulus was set at 40 ksi and the FWD load ranged from 4874 to 14,527 pounds. The results of this analysis are shown in Figures 29-31. Even though there is considerable variability in the layer moduli for the AC and base layers at a given load, the regression fit can be regarded as horizontal (based on the coefficient of determination). This implies that the two variables (layer modulus and FWD load) are independent of each other. The subgrade modulus does show more sensitivity to load than the other two layers, but not enough to seriously question the computed values.

In order to conduct further analysis of this potential influence of saturated soil conditions on backcalculated layer moduli, data from a pavement section with a known or suspected saturated subgrade condition was requested from the Washington State DOT (SR525).

3.2 SR 525 Pavement Section

The field data for this pavement section consisted of FWD (Dynatest 8000) deflection basins and boring logs at Mileposts 1.70 and 2.45 (the location is near the Alderwood Mall in Lynnwood, Washington). This information was obtained from WSDOT production data associated with the normal pavement design process. The FWD

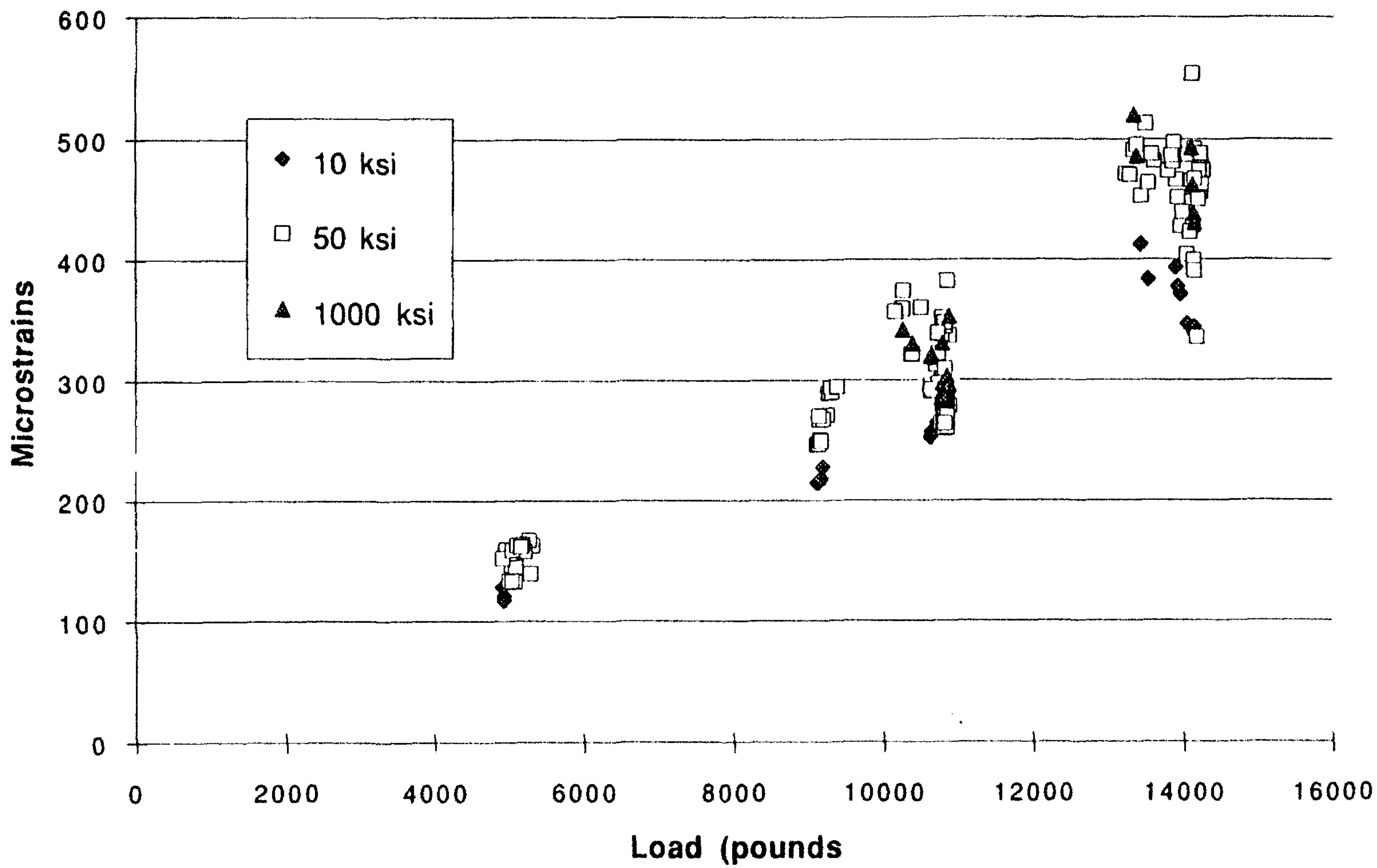


Figure 28. Calculated Horizontal Tensile Strain vs. FWD Load at Varying Stiff Layer Moduli—PACCAR Test Section

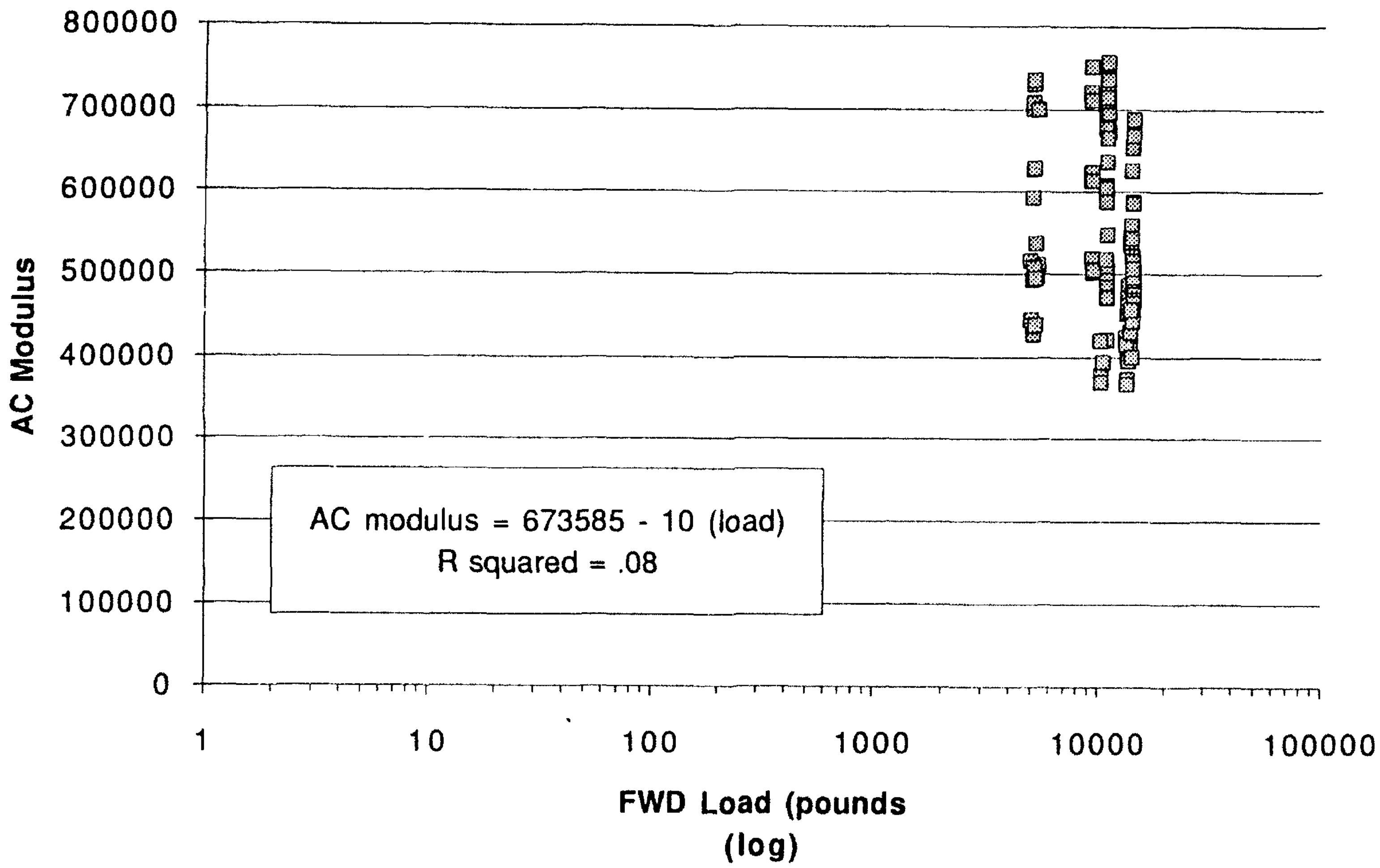


Figure 29. AC Modulus vs. FWD Load—PACCAR Test Section

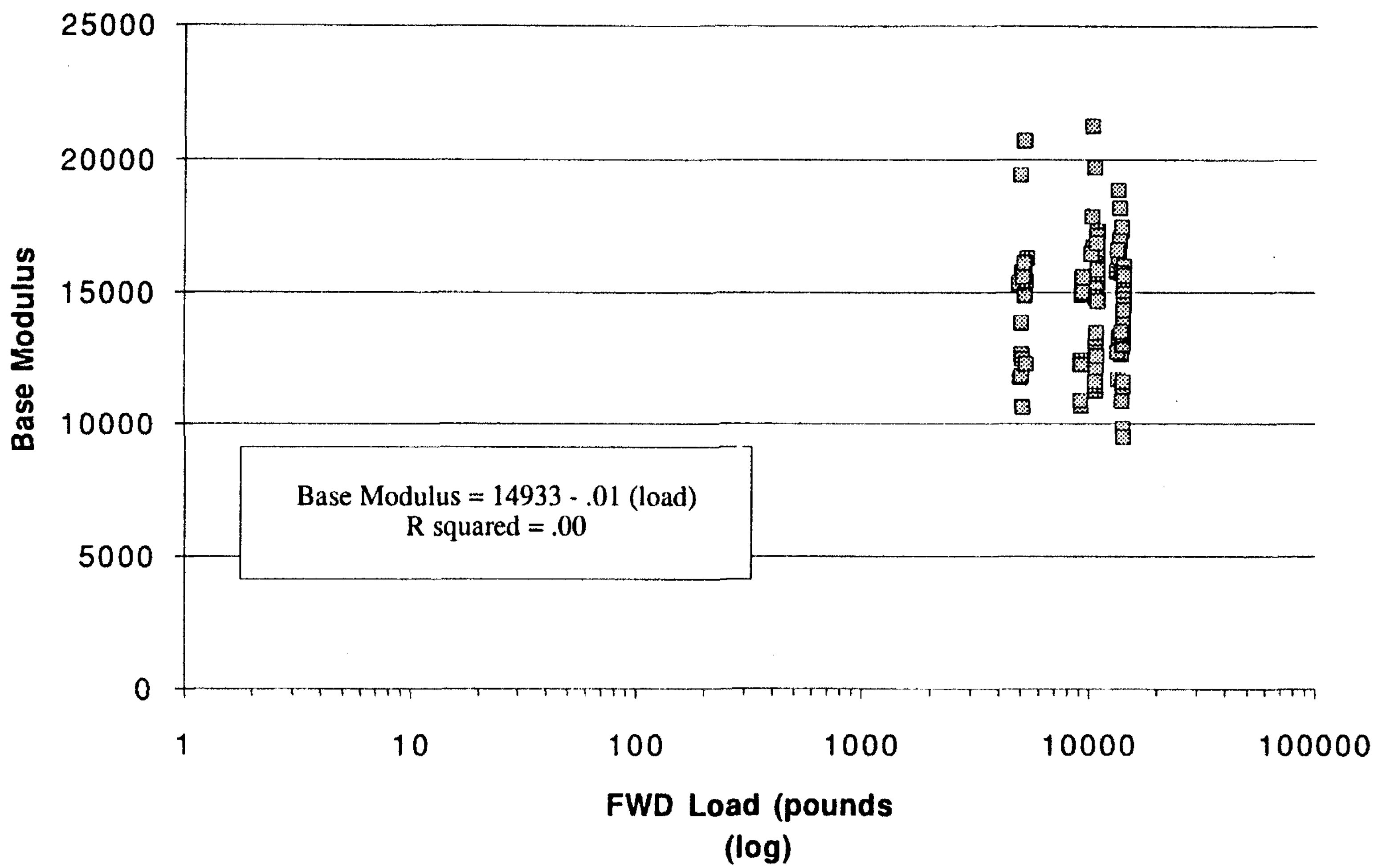


Figure 30. Base Modulus vs. FWD Load—PACCAR Test Section

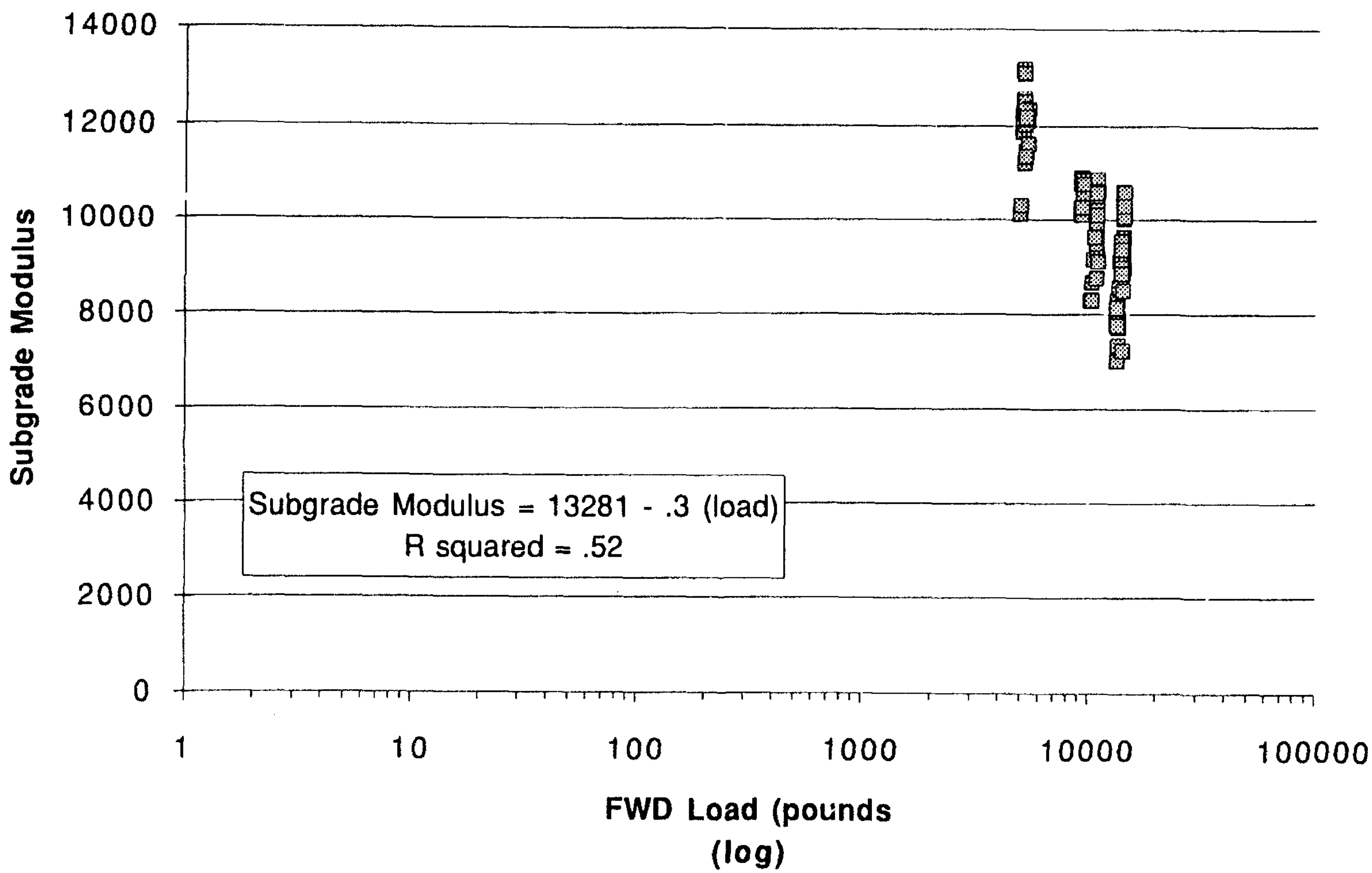


Figure 31. Subgrade Modulus vs. FWD Load—PACCAR Test Section

testing was done on April 15, 1992, with a measured mid-depth AC temperature of 45°F. The condition of the AC layer was quite variable with various amounts of fatigue and longitudinal cracking, patching, and minor rutting. The boring logs (summaries of which are shown as Figure 32) indicated no specific water table but moist/wet conditions were encountered at about 3 feet (MP 1.70) and 2 feet (MP 2.45).

The stiff layer algorithm in EVERCALC estimated a stiff layer condition at a depth of 5.9 ft for MP 1.70. This depth coincides with a transition point from a medium dense sand (22 blows per ft measured by standard penetration test (SPT)) to a very dense sand (51 blows per ft). The calculated stiff layer for MP 2.45 was 5.0 ft which coincides with a transition from a moist, dense sand (42 blows per ft) to a wet, medium dense sand (15 blows per ft).

The backcalculated layer moduli, stiff layer moduli, and associated RMS values are shown in Tables 21 and 22 for MP 1.70 and 2.45, respectively. The results for MP 1.70 appear to best match with the lower stiff layer modulus (50 ksi). An AC modulus of about 1500 ksi would be expected based on uncracked laboratory test conditions. The backcalculated AC modulus is within this range. Further, a visual inspection of the AC condition showed no cracking or rutting at this specific milepost. The base and subgrade moduli are reasonable with a low RMS level (1.0 percent average based on four deflection basins). The MP 2.45 section was quite different. The AC layer exhibited fatigue cracking and rutting, resulting in lower AC moduli. Overall, the lower stiff layer stiffness is preferred; however, the average RMS values (again, based on four deflection basins) are all rather high at this milepost.

Only 50 ksi and 1000 ksi were used as stiff layer moduli for this pavement section. While 50 ksi provides much better results than 1000 ksi, 50 ksi may not be the optimal value for the stiff layer modulus. These two moduli values were selected only to demonstrate the potential importance of the influence of saturated soil conditions.

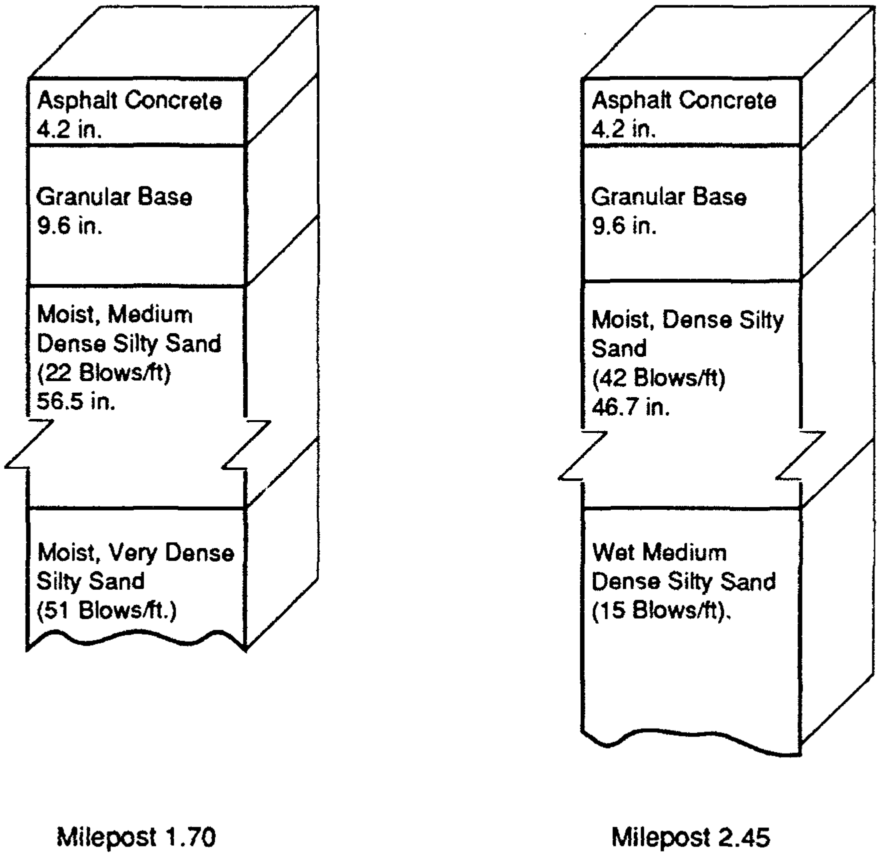


Figure 32. Cross-sections for SR 525 Pavement Sections, MP 1.70 and 2.45 [17]

Table 21. Sensitivity of Layer Moduli as a Function of Stiff Layer Modulus — SR525 Pavement Section, MP 1.70

PAVEMENT LAYERS	E_{stiff}	
	50 ksi	1000 ksi
Asphalt Concrete* (4.2 in)	1765 ksi	503 ksi
Crushed Stone Base* (9.6 in)	34 ksi	109 ksi
Subgrade* (56.5 in)	12.9 ksi	7.6 ksi
RMS(%)*	1.0	2.7

*Average of all runs

Table 22. Sensitivity of Layer Moduli as a Function of Stiff Layer Modulus — SR525 Pavement Section, MP 2.45

PAVEMENT LAYERS	E_{stiff}	
	50 ksi	1000 ksi
Asphalt Concrete* (4.2 in)	378 ksi	234 ksi
Crushed Stone Base* (9.6 in)	28 ksi	41 ksi
Subgrade* (46.7 in)	3.9 ksi	3.0 ksi
RMS(%)*	3.7	5.4

*Average of all runs

The analysis of these two sections (PACCAR and SR525) illustrates and supports the following points:

1. The stiff layer is important.
2. The Rhode and Scullion [20] algorithm provides a reasonable estimate of the depth to the stiff layer (Chapter 2, Section 6.1.2.2).
3. The stiffness of the stiff layer appears to be influenced by saturated soil conditions as well as the more obvious reasons (such as rock, and stress sensitivity of the subgrade soils).

It should be emphasized that this analysis has proved nothing other than some interesting empirical evidence but supports the backcalculation analyses done for the PACCAR test section (Section 3.1).

CHAPTER 4

INSTRUMENTATION

1. INTRODUCTION

This chapter highlights all aspects of the pavement instrumentation. Topics include the types of instruments acquired, their location in the test section, installation techniques, and the procedures used in data collection and reduction. A brief discussion of the initial validation testing is also presented.

2. ACQUISITION OF INSTRUMENTATION

The types of instruments acquired for installation in the test section were selected based on two parameters.

1. The data required to achieve the objectives of the research (see Chapter 1).
2. Installation requirements.

Because the instruments were to be installed in an existing pavement structure, this dictated that the instruments must be suitable for such an application.

Information was obtained from three sources.

- Review of literature.
- Dialog with other pavement researchers.
- Staff of the PACCAR Technical Center.

Instruments were needed to measure the following pavement responses.

- Longitudinal and transverse strain at the pavement surface.
- Longitudinal and transverse strain at the bottom of the AC layer.
- Shear strain at the pavement surface.
- Shear strain at the mid-depth of the AC layer.
- Deflection at the pavement surface.
- Deflection at the bottom of the AC layer.
- Deflection two inches below the top of the aggregate base.

- Deflection two inches below the top of the subgrade.
- Pavement temperature at various depths throughout the structure.

A foil-type gauge manufactured by Micro-Measurement was chosen to measure the various strain responses. An Australian-made Multidepth Deflectometer (MDD), used extensively by the Australian Road Research Board, with four linear variable differential transformers (LVDTs) and a piezoresistive accelerometer, was selected to measure pavement layer deflections. For temperature data, a multi-sensor thermistor-based temperature probe manufactured by Measurement Research Corporation was chosen.

3. LAYOUT OF INSTRUMENTATION

A total of 102 (excluding temperature compensation gauges) of the foil-type strain gauges (hereafter referred to as strain gauges) and one MDD were installed in the pavement section. The applications for the strain gauges are shown in Table 23. Each axial strain gauge is designated by a three element name. The first element represents the gauge number in the series of gauges at the same location in the AC layer and oriented in the same direction. The second element represents the gauge's location in the AC layer. An "S" represents the surface of the AC layer; a "B" the bottom of the AC layer. The third element identifies the orientation of the measurement direction. An "L" represents the longitudinal direction; a "T" the transverse. An example is the gauge 3BL. This gauge is the third gauge which measures longitudinal strain at the bottom of the AC layer.

The shear slot gauges are also identified by a 3 element name. The first element represents the gauge number. The second and third elements for all these gauges are the letters "SS" which stand for "shear slot."

The shear core gauges have a two element name. The first element is the gauge number. The second element is an "S" for "shear". A complete list of all the gauge

Table 23. Distribution of Strain Gauges - PACCAR Test Section

TYPE OF INSTALLATION	NUMBER OF LOCATIONS	NUMBER OF LONGITUDINAL GAUGES PER LOCATION		NUMBER OF TRANSVERSE GAUGES PER LOCATION		NUMBER OF SHEAR GAUGES PER LOCATION	TOTAL
		AT SURFACE	AT BOTTOM	AT SURFACE	AT BOTTOM		
Axial Core	5	1	1	1	1		20
Shear Core	10					2	20
Shear Slot	1					20	20
Independent Surface	4			1			4
Independent Surface	38	1					38
TOTALS	67						102

designations and their appropriate gauge location and measurement orientation is contained in Table 24.

The physical layout of these gauges at the test section is shown at Figure 33. The layout was designed to ensure the collection of critical pavement responses for both layer elastic and finite element analysis methods. The axial cores were displaced laterally to allow collection of strain measurements from both wheel paths and the approximate centerline of the wheel base. The longitudinally oriented surface strain gauges were specifically designed to evaluate the dynamic response of a truck as it travels down the pavement section.

4. INSTALLATION OF INSTRUMENTATION

A four inch diameter core barrel was used to cut the 15 cores (5 axial, 10 shear) from the pavement section. These 15 core samples were used to perform the materials testing discussed in Chapter 3. The strain gauges were mounted on cores that were removed from the adjacent lane of the pavement section using a 4.5 inch core barrel. This procedure resulted in a clearance of only 1/16 of an inch between the sides of the core and the hole in the pavement. One quarter of an inch was cut off the top and bottom of the cores to provide a smooth surface for mounting the gauges. All pavement coring and cutting was performed by WSDOT.

4.1 Axial Strain Cores

A slot 1/8 inch wide by 1/4 inch deep was cut along the length of the core as a path for the necessary wiring (see Figure 34). Two gauges were glued to each end of the core using a thin layer of epoxy. These two gauges were in the same perpendicular plane and mounted at a 90 degree angle to each other forming an "L". One gauge measured transverse strain, the other longitudinal strain. Coring resulted in varying amounts of aggregate loss from the base course. The void resulting from this aggregate loss and reduced core thickness was filled with the same epoxy used to bond the core back to the

Table 24. Description of Gauge Designations - PACCAR Test Section

GAUGE DESIGNATION	CORE NUMBER	GAUGE LOCATION	MEASUREMENT DIMENSION
3ST	Axial Core 1	Surface of the AC	Transverse
3SL	Axial Core 1	Surface of the AC	Longitudinal
1BT	Axial Core 1	Bottom of the AC	Transverse
1BL	Axial Core 1	Bottom of the AC	Longitudinal
1ST	N/A	Surface of the AC	Transverse
1SL	N/A	Surface of the AC	Longitudinal
2ST	N/A	Surface of the AC	Transverse
2SL	N/A	Surface of the AC	Longitudinal
4ST	N/A	Surface of the AC	Transverse
4SL	N/A	Surface of the AC	Longitudinal
5ST	Axial Core 2	Surface of the AC	Transverse
5SL	Axial Core 2	Surface of the AC	Longitudinal
2BT	Axial Core 2	Bottom of the AC	Transverse
2BL	Axial Core 2	Bottom of the AC	Longitudinal
6ST	N/A	Surface of the AC	Transverse
6SL	N/A	Surface of the AC	Longitudinal
7ST	Axial Core 3	Surface of the AC	Transverse
7SL	Axial Core 3	Surface of the AC	Longitudinal
3BT	Axial Core 3	Bottom of the AC	Transverse
3BL	Axial Core 3	Bottom of the AC	Longitudinal
8SL	N/A	Surface of the AC	Longitudinal
9SL	N/A	Surface of the AC	Longitudinal
8ST	Axial Core 4	Surface of the AC	Transverse
10SL	Axial Core 4	Surface of the AC	Longitudinal
4BT	Axial Core 4	Bottom of the AC	Transverse
4BL	Axial Core 4	Bottom of the AC	Longitudinal
11SL	N/A	Surface of the AC	Longitudinal
12SL	N/A	Surface of the AC	Longitudinal
13SL	N/A	Surface of the AC	Longitudinal
14SL	N/A	Surface of the AC	Longitudinal
15SL	N/A	Surface of the AC	Longitudinal
16SL	N/A	Surface of the AC	Longitudinal
9ST	Axial Core 5	Surface of the AC	Transverse
17SL	Axial Core 5	Surface of the AC	Longitudinal
5BT	Axial Core 5	Bottom of the AC	Transverse
5BL	Axial Core 5	Bottom of the AC	Longitudinal
18SL	N/A	Surface of the AC	Longitudinal
19SL	N/A	Surface of the AC	Longitudinal
20SL	N/A	Surface of the AC	Longitudinal
21SL	N/A	Surface of the AC	Longitudinal
22SL	N/A	Surface of the AC	Longitudinal
23SL	N/A	Surface of the AC	Longitudinal
24SL	N/A	Surface of the AC	Longitudinal
25SL	N/A	Surface of the AC	Longitudinal

Table 24. Description of Gauge Designations - PACCAR Test Section (continued)

GAUGE DESIGNATION	CORE NUMBER	GAUGE LOCATION	MEASUREMENT DIMENSION
26SL	N/A	Surface of the AC	Longitudinal
27SL	N/A	Surface of the AC	Longitudinal
28SL	N/A	Surface of the AC	Longitudinal
29SL	N/A	Surface of the AC	Longitudinal
30SL	N/A	Surface of the AC	Longitudinal
31SL	N/A	Surface of the AC	Longitudinal
32SL	N/A	Surface of the AC	Longitudinal
33SL	N/A	Surface of the AC	Longitudinal
34SL	N/A	Surface of the AC	Longitudinal
35SL	N/A	Surface of the AC	Longitudinal
36SL	N/A	Surface of the AC	Longitudinal
37SL	N/A	Surface of the AC	Longitudinal
38SL	N/A	Surface of the AC	Longitudinal
39SL	N/A	Surface of the AC	Longitudinal
40SL	N/A	Surface of the AC	Longitudinal
41SL	N/A	Surface of the AC	Longitudinal
42SL	N/A	Surface of the AC	Longitudinal
43SL	N/A	Surface of the AC	Longitudinal
1S	Shear Core 1	Just Below Surface	Shear
2S	Shear Core 2	Just Below Surface	Shear
3S	Shear Core 3	Just Below Surface	Shear
4S	Shear Core 4	Just Below Surface	Shear
5S	Shear Core 5	Just Below Surface	Shear
6S	Shear Core 6	Just Below Surface	Shear
7S	Shear Core 7	Just Below Surface	Shear
8S	Shear Core 8	Just Below Surface	Shear
9S	Shear Core 9	Just Below Surface	Shear
10S	Shear Core 10	Just Below Surface	Shear
1SS	Shear Slot	Just Below Surface	Shear
2SS	Shear Slot	Just Below Surface	Shear
3SS	Shear Slot	Just Below Surface	Shear
4SS	Shear Slot	Just Below Surface	Shear
5SS	Shear Slot	Just Below Surface	Shear
6SS	Shear Slot	Just Below Surface	Shear
7SS	Shear Slot	Just Below Surface	Shear
8SS	Shear Slot	Just Below Surface	Shear
9SS	Shear Slot	Just Below Surface	Shear
1OSS	Shear Slot	Just Below Surface	Shear

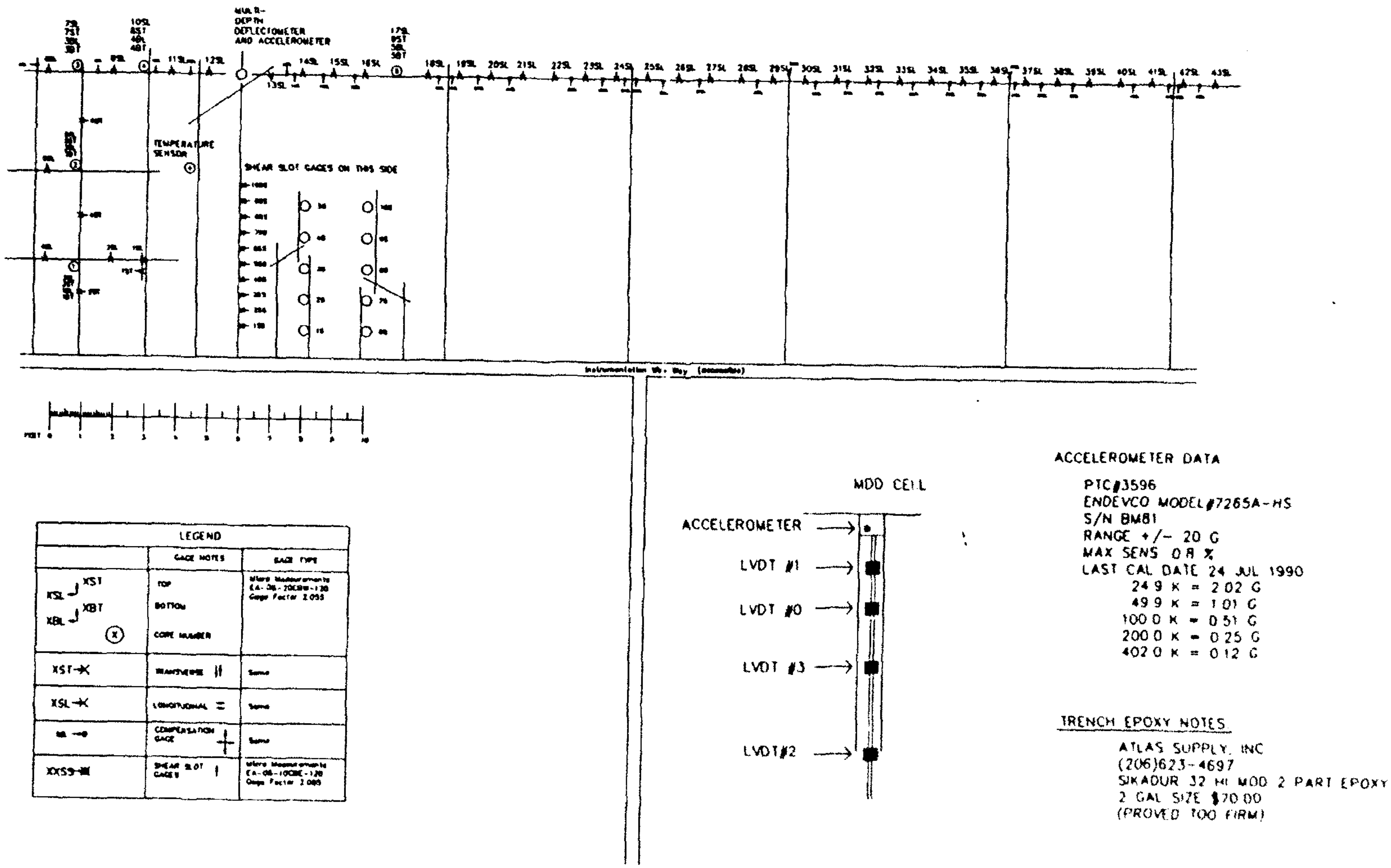


Figure 33. PACCAR Pavement Test Track Layout

pavement section. To ensure the epoxy completely filled the gap between the sides of the core and the hole in the pavement, the core was pushed into the hole until epoxy oozed up along the sides of the core. In most cases this caused the top of the core to be below the surface of the pavement and epoxy was also used to fill this void. As a result, the gauges mounted on the surface of the cores were actually underneath the epoxy layer on top of the core.

4.2 Shear Strain Cores

The cores were cut in half lengthwise to provide a mounting surface for the shear gauges. A slot 1/8 of an inch wide by 1/2 inch deep was cut across the diameter of the top of the core to provide a path for the lead wires (see Figure 35). The procedures used for gauge mounting and core installation were the same as those used for the axial cores. The only difference was that a layer of epoxy was placed between the two core halves just prior to their insertion into the hole in the pavement to bond them back together.

4.3 Shear Slot

A long slot shaped like an inverted "L" was cut perpendicular to the section from about the centerline to the shoulder of the pavement. The slot dimensions are shown in Figure 36. Epoxy was used to glue the shear gauges along the vertical face of the cut at six inch spacing. The lead wires were laid in the bottom of the slot and it was filled with epoxy.

4.4 Surface Gauges

A series of inverted "L" shaped slots were cut into the section for mounting the longitudinal and transverse surface gauges. The slot was formed by two cuts made side by side. One was 0.25 inch deep and 0.5 inch wide. The other was 0.5 inch wide by 1 inch deep (see Figure 37). The gauges were glued in a horizon position on the ledge formed by the width of the shallower cut. As in the shear slot, the lead wires were laid at the bottom of the slot and the slot was filled with epoxy.

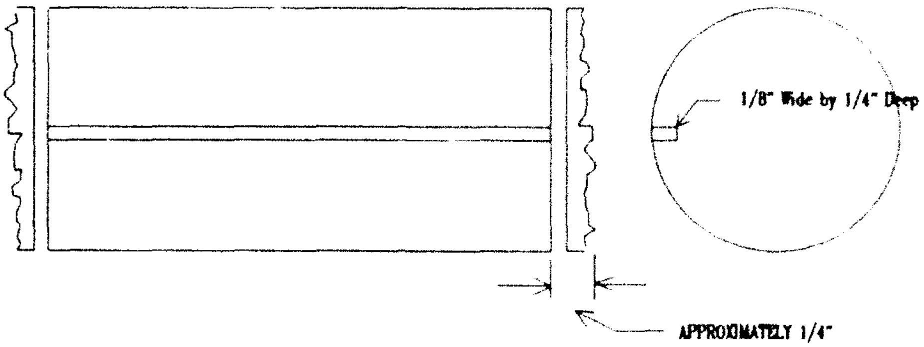


Figure 34. Saw Cutting Details for Axial Strain Cores

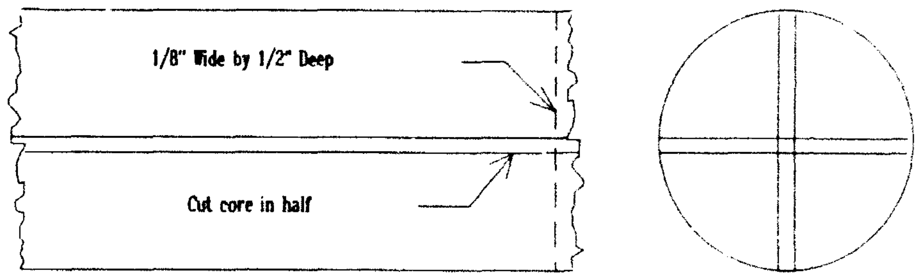


Figure 35. Saw Cutting Details for Shear Strain Cores

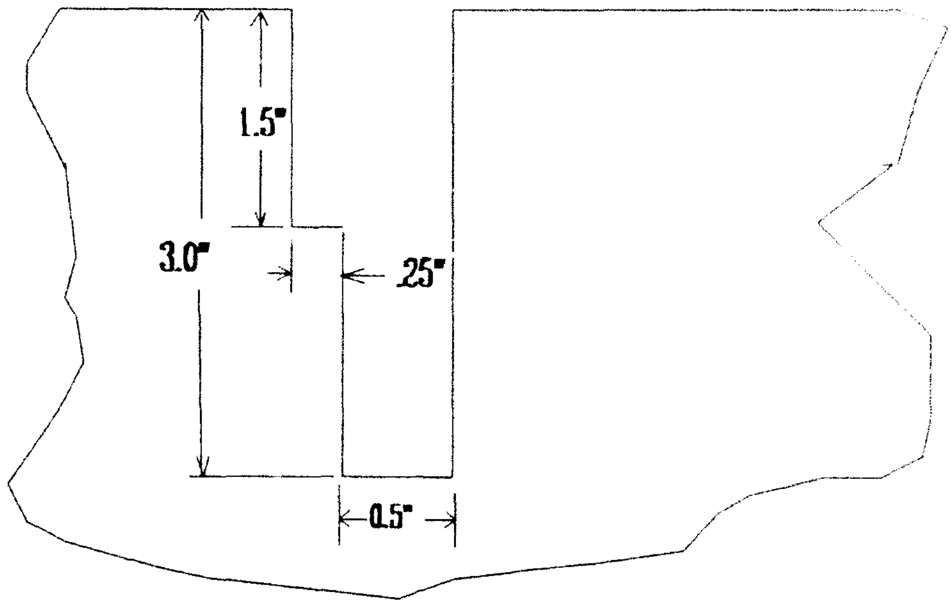


Figure 36. Shear Gauge Slot Dimensions

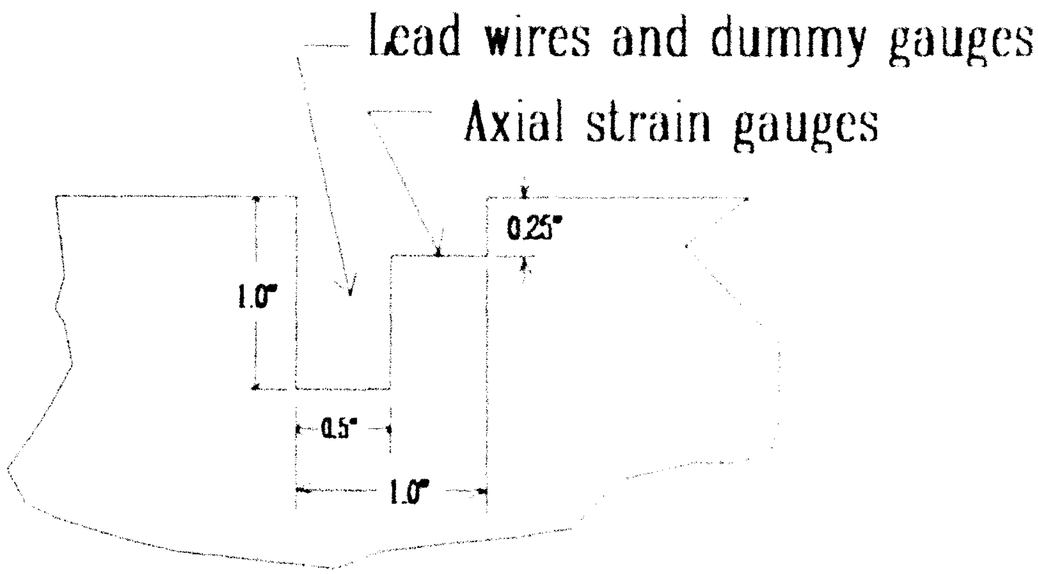


Figure 37. Surface Gauge Slot Dimensions

4.5 Temperature Compensation Gauges

Temperature compensation gauges were installed in both axial strain cores and independent surface strain gauge applications. A separate strain gauge was embedded in a layer of room temperature vulcanization (RTV) silicon sealant and mounted on a strip of asphalt concrete. The RTV isolates the temperature compensation gauge from the bending in the AC caused by temperature. The active gauge and the temperature compensation gauge were connected to adjacent arms of the Wheatstone bridge circuit. Use of the two gauges cancels the voltage output from the active gauge due to bending caused by a temperature change in the AC. [43] One of these gauges was placed in the 1 inch slot parallel to each surface strain gauge. A temperature compensation gauge was also mounted in series with each of the four active gauges per axial strain core. This resulted in a total of eight gauges installed at each axial core (four active gauges, four temperature compensation gauges). The shear gauges used in both the shear slots and the shear cores were self compensating and did not require a temperature compensation gauge. The temperature compensation gauges also eliminated the non-linearity problems associated with completing only one arm of a Wheatstone bridge circuit. [43]

4.6 Temperature Probe

The temperature probe consists of a one inch (outside diameter) clear polyvinyl chloride (PVC) tube filled with a transparent epoxy. Inside the tube are 20 thermistor temperature sensors at various locations along its 50 inch length. The locations of the sensors within the pavement structure are shown in Table 25. The probe is read manually using a hand held read-out unit and has an accuracy of ± 0.2 degrees Celsius. The probe was placed inside a 1.5 inch schedule 200 PVC pipe which was permanently mounted in the pavement section. The location of the probe is shown in Figure 33.

4.7 Multidepth Deflectometer

Installation of the MDD was a very difficult and time consuming process. The unit was originally designed for laboratory installation so both the hardware and

Table 25. Temperature Sensor Locations - PACCAR Test Section

SENSOR NUMBER	DEPTH FROM PAVEMENT SURFACE (inches)
1[1,2]	1.5
2[1]	4
3	5
4	6
5	7
6	8
7	9
8	10
9	11
10	12
11	13
12	14
13	16
14	19
15	25
16	31
17	37
18	43
19	49
20	51.5

Notes:

[1]Sensor exposed to air.

[2]Sensor reliability uncertain.

installation procedures had to be modified for field installation. The manufacturer stated that the success rate for installation is about 75 percent. [44] The complete installation requires at least two personnel for 2 days. The steps taken to install the MDD were as follows.

Day 1

1. A 1.5 inch core sampler was used to excavate a hole approximately 7 feet deep. This device uses a 140 pound drop hammer to drive a 1.5 inch steel rod into the ground. The major concern for this step is to ensure a firm side wall for securing the LVDT anchor points.

2. A 2.5 inch diameter hole was drilled to a depth of one inch into the AC layer for installation of the top cap. The top cap must be mounted flush with the pavement surface to avoid point loading. [45]

3. A rubber tube was placed in the hole using an installation tool provided by the manufacturer. The tube was then grouted in place using the Sikadur® epoxy (see Section 4.9.2). Use of the epoxy did result in a successful installation, but it was very viscous and difficult to use. It is recommended that another material be used in future installations. A rubber grout has been used successfully by other researchers. [45]

4. The ground anchor rod was screwed into the ground anchor. Sikadur® epoxy was then poured down the hole and the ground anchor was lowered into the epoxy. Weights should be hung on top of the rod to ensure the anchor does not float out of the epoxy. More epoxy was then poured down the hole. Installation was halted at this point to allow the epoxy to cure.

Day 2

5. The individual anchor points for each of the four LVDTs were installed at the appropriate depths.

6. A reference rod was then installed to guide the LVDTs into the correct position. The LVDTs were secured using a specially designed tool.

7. The transducer housing and accelerometer were installed.

8. The accelerometer and LVDT lead wires were connected to the electrical panel.

9. The unit was calibrated using a series of thin washers placed in sequence between the four spring loaded heads of the LVDTs and the top of the anchor rods.

A typical installation of a MDD is shown in Figure 38.

4.8 Wiring Slots and Electrical Panel

Numerous slots (0.5 inch wide by 1 inch deep) were cut parallel and perpendicular to the test section to accommodate the enormous amount of lead wires from all the gauges. At least one, and in some cases two, lead wire slots bisected the hole in the pavement formed by the core (see Figure 39). The slots must be cut after the cores are removed to prevent deformation of the core and to ensure proper alignment of the cut. These slots allowed all the wiring to be channeled into a metal conduit (6 inches wide x 2 inches deep x 40 inches long) running parallel to the section just inside the shoulder lane. The conduit is rectangular in shape and has a removable cover. From the conduit, all the lead wires terminate in an electrical panel mounted just off the shoulder of the section. The panel is inside a standard electrical cabinet mounted approximately 5 feet above the ground. All Wheatstone bridge circuits were completed at the panel. The panel also provides the connectors for data collection instrumentation. The electrical panel layout is shown in Figure 40.

4.9 Epoxy

There were two types of epoxy used in gauge installation. One type was used to mount the gauges to the asphalt concrete, whether it was cores or slots, and the other was used to bond cores to the pavement or fill in slots cut in the pavement.

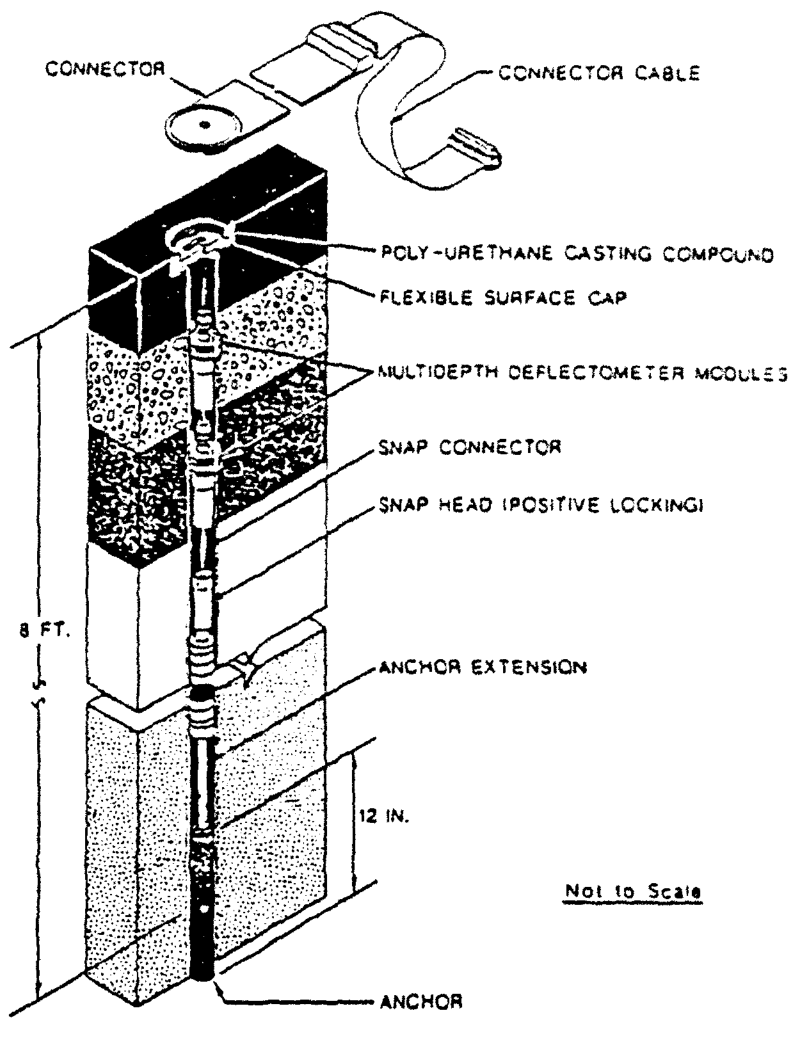


Figure 38. Typical Installation of a Multidepth Deflectometer [45]

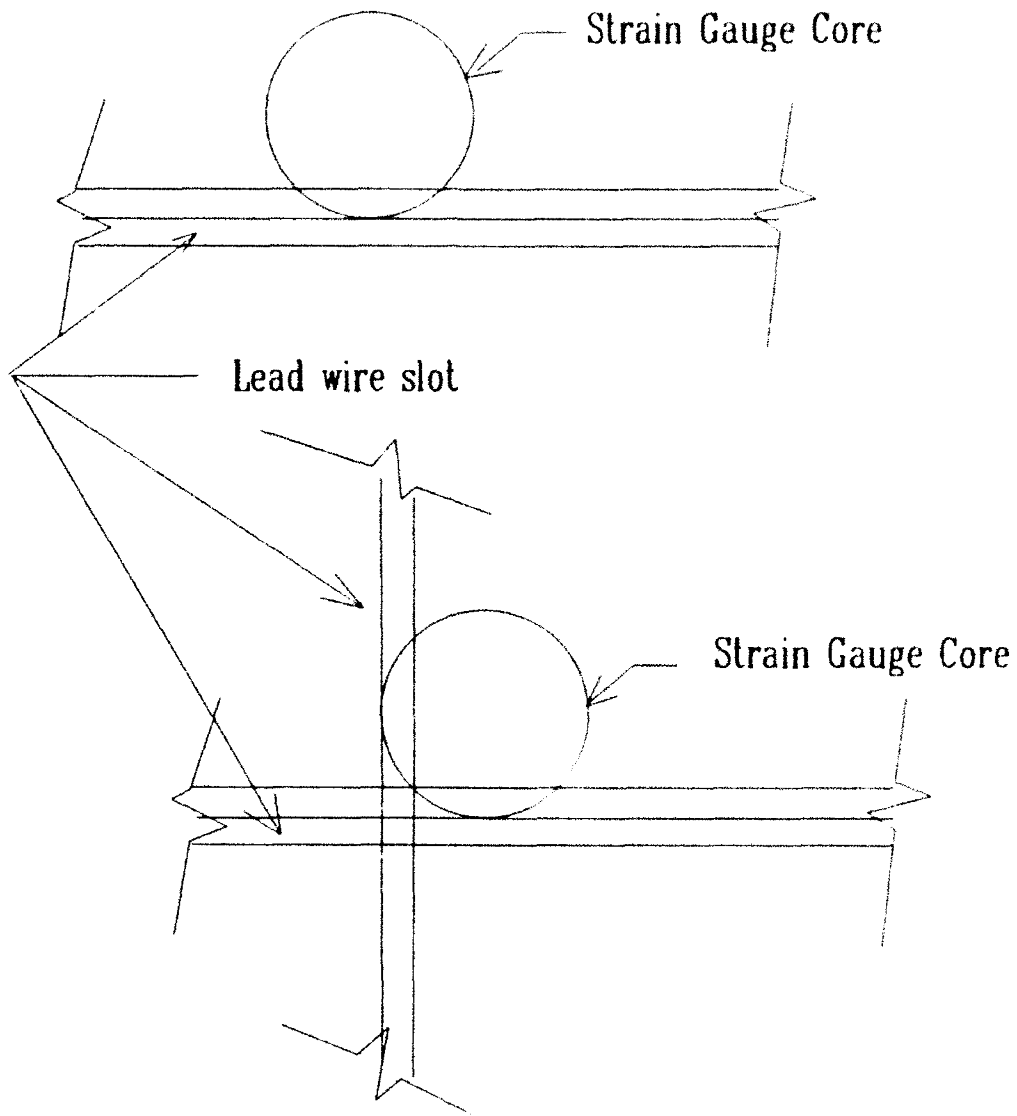


Figure 39. Plan View of Lead Wire Slots Bisecting Core Holes

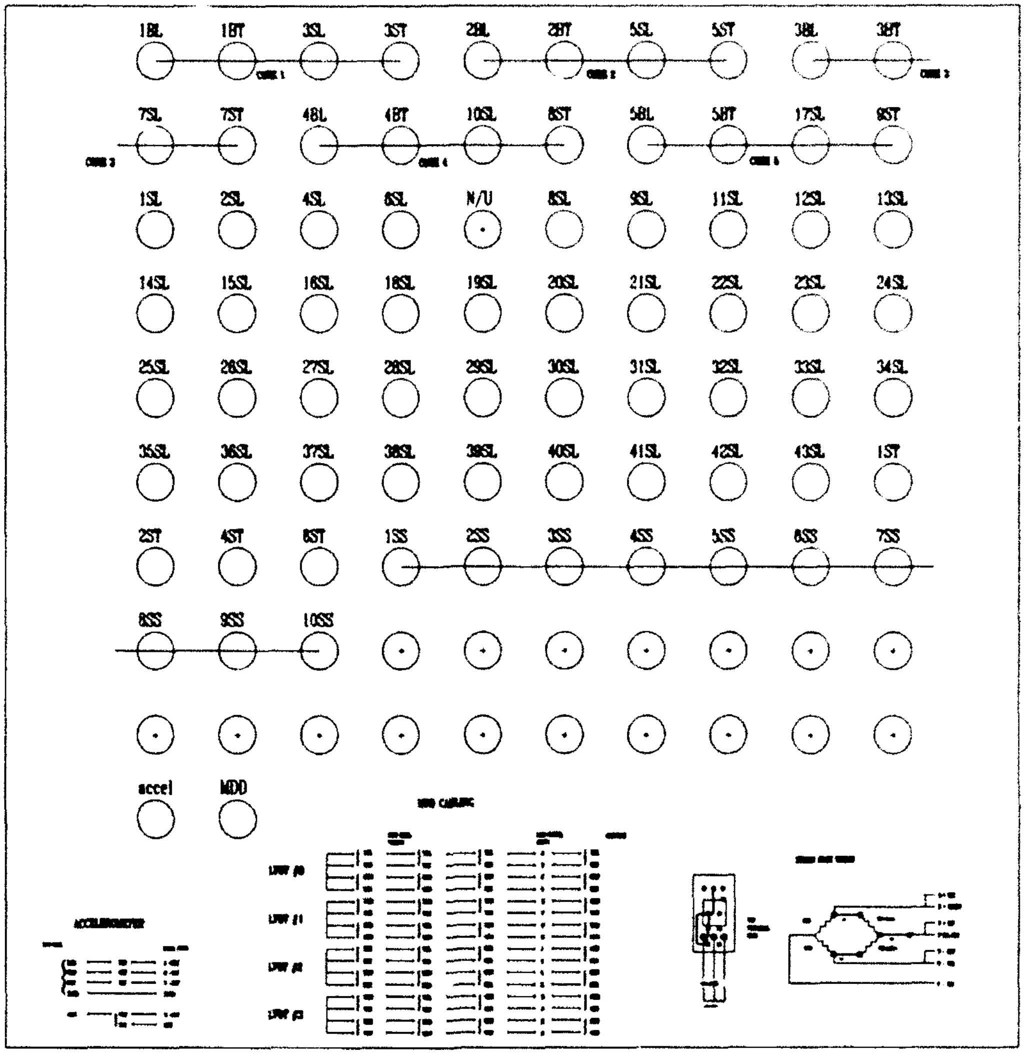


Figure 40. Electrical Panel Layout

4.9.1 Gauge Epoxy

The epoxy used to glue the strain gauges to the AC was Micro-Measurement M-Bond AE-10. This epoxy system is designed for strain gauge applications [46]; however, the product manufacturer does not publish a modulus of elasticity for this adhesive. [47] The layer of epoxy between the gauge and AC surface is so thin that its effect on measured strain is probably insignificant, particularly in view of the other uncertainties in this measurement environment. The sensitivity of epoxy modulus to temperature is also unknown. [47] Should these uncertainties become more important, laboratory testing could be used to establish the epoxy stiffness and temperature sensitivity.

4.9.2 Pavement Epoxy

The selection of this epoxy was cr ical. As mentioned in Chapter 2 [27], the modulus of the epoxy should match that of the AC as closely as possible. Unfortunately, technical and research reports describing previous use of epoxy in instrumented pavement core applications did not provide any details on the specific type or material properties of the epoxy used. From discussions with the Turner-Fairbank Highway Research Center, they have recently used a 3M® Structural Epoxy; however, the modulus of this product is unknown.

After further research, Sikadur® 32 Hi Mod 2 part epoxy was chosen. Originally, it was understood that the modulus of this epoxy was 500 ksi (approximately the same modulus for Class B ACP at 72°F) and that value was used when calculating theoretical strain responses due to pavement loading (see Chapter 5, Sections 3.1 and 3.2). Near the end of this research, it was discovered that the actual modulus of this epoxy is 440 ksi under ideal mixing and curing conditions (73°F and 50% relative humidity). [48] It is known that the curing temperature ranged from 80 to 90°F; however, the relative humidity was unknown. The effect of these less than ideal conditions on the modulus of the epoxy is unknown. The modulus could be determined under laboratory testing but a comparison of the results to the in situ material would be uncertain. In order to duplicate the stiffness of the in situ material, the same proportions of the two components (as originally mixed) would have to be mixed under the same curing conditions. It is believed that this is both impractical and unnecessary. This is discussed further in Chapter 5, Section 3.2. There was some minor cracking in the epoxy within the first few weeks of installation. This cracking was caused by an excessive volume of epoxy being used to fill the 4 inch diameter of the space above and below the core. [49] When the epoxy is used to anchor cylindrical objects, the hole diameter can not exceed .25 inch. [48] Exceeding this diameter causes "creep" which results in cracking. [49] The cracking stabilized almost immediately and no further problems have been experienced. Approximately 10 gallons of this epoxy were used throughout the section.

4.10 Data Acquisition and Signal Conditioning

The proper data acquisition system is the key to obtaining meaningful data. [39] Data acquisition and conditioning consist of three major components: hardware, software, and acquisition parameters.

4.10.1 Hardware

Hardware consists of computers and signal conditioners. The following hardware was used during testing.

- Microcomputer (IBM compatible)

  80286 microprocessor
  data acquisition board
  fixed disk
  serial/parallel port
  multichannel analog-to-digital interface boards
  color monitor

- Signal Conditioner

  Signal conditioner mainframe, Pacific Industries, PN # R16DC

  Signal conditioner modules, Pacific Industries, PN # 3210 (1 per channel)

The signal conditioner provides the excitation voltage for the gauge circuitry and amplifies the millivolt signal from the transducers to a voltage that can be more easily recorded and analyzed. A low pass (20 Hertz) filter was used in all data acquisition except during the February 1993 FWD testing. It was found that this filtering was a desirable method to reduce electrical noise.

4.10.2 Software

The HEM Snapshot software package was used to control the hardware and acquire the data from the strain gauges. The software stores the data in a binary format but can be used to convert the binary format to ASCII. The signal from any gauge can also be displayed on the monitor immediately after collection. This very useful capability provides for immediate verification of signal quality and can help prevent acquisition of "problem" data. The software also appends appropriate "header" information (date, time, testing parameters) to the data file before writing to the fixed disk.

4.10.3 Data Acquisition Parameters

There are five basic parameters for data acquisition. The parameters and the associated values used in data collection are shown in Table 26.

Table 26. Summary of Data Acquisition Parameters

	Test Series			
DATA ACQUISITION PARAMETER	October 1991 FWD Testing	May 1992 Truck Testing	June 1992 FWD Testing	February 1993 FWD Testing
Sample Rate (Hertz)	512	128, 256	512	512
Sweep Time (seconds)	4	10, 5	10	4
Voltage Range	± 1	± 1	± 1	± 1
Gain	1	5	5	5
Shunt Resistance (ohms)	100k	200k	200k	200k

4.11 Pilot Testing

Initial testing of the instrumented section used a calibration trailer towed at various speeds and a FWD. The purpose of the testing was to monitor the relative activity of each gauge under similar loads and speeds from moving wheel and FWD loads. Analysis of this data provided an initial assessment of gauge performance and survivability. While a detailed analysis was not conducted, the general results indicated a successful installation had been accomplished.

CHAPTER 5

DATA ANALYSIS

1. INTRODUCTION

This chapter begins with a discussion of the procedure used to convert the raw data (voltage) collected by the strain gauges to engineering units (microstrains). Data collected during two series of FWD testing is analyzed and a comparison of measured to calculated strains is presented. A comparison is also made between measured longitudinal and transverse strains at the surface and bottom of the AC layer for one of the FWD tests. Because of their importance to mechanistic-empirical design, only strains measured by the axial cores in the wheel paths (Cores 1, 3, 4, and 5) will be presented. Core 2 is omitted due to its location (centerline of the section) and the inability to establish realistic effective layer thicknesses for the epoxy above and below the core (see Section 3.1).

2. GENERAL PROCEDURE FOR REDUCTION AND CONVERSION OF MEASURED STRAIN RESPONSES

When a load is applied to the pavement surface directly above a strain gauge, the pavement deflects under the load. This deflection causes the AC layer to bend which in turn causes the strain gauge to elongate and thus induces a change in its resistance. A Wheatstone bridge circuit is used to convert the change in resistance to a voltage signal that can be measured by the instrumentation discussed in Chapter 4. [43] The voltage is then converted to engineering units (microstrains) through the following steps.

1. A system calibration factor is determined by dividing the calibration strain value of the shunt resistor used to calibrate the measurement system by the voltage used to calibrate the system (shunt voltage).

2. A channel calibration factor for each channel is determined by taking the system calibration factor from Step 1 and dividing it by the calibration voltage of the bridge produced when the shunt resistance is applied to that channel.

3. The data series collected during a load application is then zeroed by subtracting a zero offset for each channel representing an average of the first forty data points from each individual data point. This type of zero procedure accounts for any "zero shift" in the data between initial system calibration and actual data collection.

4. Microstrains are then computed by multiplying the result of Step 3 by the channel calibration factor computed in Step 2. The resulting data series can be plotted for a strain-time trace or the maximum strain value can be determined.

An example of this procedure for one channel is shown below where:

- calibration strain value of shunt resistor = 291.1 microstrains,
- system calibration voltage (shunt voltage) = .727 volts,
- channel calibration voltage = .772 volts,
- channel zero offset = .08 volts, and
- maximum voltage recorded under a 10k (pound) FWD load = .27 volts.

<u>Step 1</u>

$$\text{system calibration factor} = \frac{\text{calibration strain value of shunt resistor}}{\text{shunt voltage}}$$

$$= \frac{291.1 \text{ microstrains}}{.727 \text{ volts}}$$

$$\approx 400 \text{ microstrains/volt}$$

<u>Step 2</u>

$$\text{channel calibration factor} = \frac{\text{system calibration factor}}{\text{channel calibration voltage}}$$

$$= \frac{400 \text{ microstrains/volt}}{.772 \text{ volts}}$$

$$\approx 518 \text{ microstrains/volt}$$

Step 3

zeroed voltage = measured voltage channel zero offset

= .27 volts - .08 volts

= .19 volts

Step 4

measured strain under the FWD load channel calibration factor (zeroed voltage)

= 518 microstrains volt (.19 volts)

= 98 microstrains

The raw data was recorded in a binary format. Because Microsoft® Excel was used to perform the data reduction, the HEM Snapshot software was used to convert the data to an ASCII format so it could be read by Excel. Some of the data was also converted to ASCII using a basic program.

As noted by Sebaaly et al. [39], data conversion and reduction was a time consuming process. This is mainly due to the volume of data. Four seconds of data collected during one FWD drop at one gauge represents 2000 data points. One data file consists of 16 times (16 channels) this amount of data (about 600k bytes).

While this data reduction and conversion process was automated, visual inspection and engineering judgment were used at critical stages of the analysis to ensure that the reduction and conversion process did not introduce any inaccuracies in the output.

3. FWD TESTING OCTOBER 10, 1991

The WSDOT Dynatest FWD was used to conduct deflection testing over the entire test section. Testing was performed in a grid of 61 drop locations totaling 130 drops with more extensive testing on the five instrumented axial cores. As previously discussed in Chapter 3, Section 3.1, EVERCALC 3.3 was used to backcalculate layer moduli from the deflection data. It was decided that a stiff layer modulus of 40 ksi best represented the in situ conditions and as such was used in the backcalculation procedure. The layer moduli (mean values) as presented in Chapter 3, Section 3.1 were used as representative of any location in the section (descriptive statistics are contained in Table 27).

3.1 Effective Layer Thicknesses

The first step in analyzing the strain data collected during this testing was to model the effect that the epoxy above and below each core would have on the measured strains. It was determined that the most practical method to accomplish this would be to determine an effective thickness for each pavement layer based on the strains measured under FWD loading.

The original AC and base course thicknesses were accurately measured during coring and installation of the MDD. The approximate thicknesses of the epoxy on top of and below each core were also known, but needed to be refined because of the inability to physically measure the epoxy thicknesses. The effective layer thicknesses for axial Cores 1, 3, 4, and 5 are shown in Table 28. In all cases, the effective thickness of the AC layer is 4.9 inches. This was calculated by subtracting the 0.5 inches (0.25 removed from each end) trimmed from each core for gauge installation. The effective thicknesses of each epoxy layer were determined by varying the thickness of the epoxy on top of and below each core until the theoretical strain calculated from linear elastic theory (CHEVPC) was similar to the strain measured by the gauges installed in the pavement section. At Core 2, measured strains were only half of the calculated values with epoxy thicknesses modeled at 1.5 inches on top of the core and none below the core. These theoretical thicknesses are unrealistic given the known approximate thicknesses and as a result, no further analysis of Core 2 was conducted. The effective thickness of the base course was computed by subtracting the combined thicknesses of the AC and epoxy layers from the original thickness (13 inches). The total thickness of the top four layers was subtracted from the average depth to stiff layer for each core as predicted by EVERCALC to

Table 27. Descriptive Statistics for Backcalculated Layer Moduli—
October 1991 FWD Testing

PAVEMENT LAYERS	Layer Modulus (psi)		
	AC	Base	Subgrade
Mean*	562,800	14,800	10,200
Standard Deviation*	113,700	2,400	1,200
Minimum*	368,100	9,500	7,000
Maximum*	757,800	21,300	13,200
Number of Drops*	120	120	120

Notes:
* RMS <= 2.5%
Stiff Layer Modulus set at 40 ksi.

Table 28. Effective Pavement Layer Thicknesses Based on October 1991 FWD Data—
Axial Cores 1, 3, 4, and 5

PAVEMENT LAYERS	AXIAL CORE			
	1	3	4	5
Epoxy	0.4 in.	0.25 in.	0 in.	0.6 in.
AC	4.9 in.	4.9 in.	4.9 in.	4.9 in.
Epoxy	0.4 in.	1.25 in.	0.5 in.	0.6 in.
Base	12.7 in.	12.0 in.	13.0 in.	12.3 in.
Subgrade	42.7 in.	46.0 in.	46.1 in.	43.8 in.
Stiff Layer	Semi-Infinite	Semi-Infinite	Semi-Infinite	Semi-Infinite

determine the subgrade thickness. A summary of the stiff layer depths for each axial core is contained in Table 29. It should be stressed that these are effective layer thicknesses for their respective location along the test section. It was not possible to physically validate these thicknesses.

3.2 Calculated Strains

As mentioned previously, the linear elastic program, CHEVPC, was used to calculate the theoretical strains under the various FWD loading conditions. The AC, base, and subgrade layer moduli (mean values) backcalculated by EVERCALC with a stiff layer modulus of 40 ksi were used as input to CHEVPC. The modulus of the Sikadur® epoxy was set at 500 ksi based on the discussion in Chapter 4, Section 4.9.2. While the exact modulus of the Sikadur® epoxy is unknown, 500 ksi is a reasonable assumption based on nondestructive test results and manufacturer's information. Strain calculated at the surface and bottom of the AC layer is a result of the compensating effect of the effective thickness and modulus of the epoxy. Given the procedure used to calculate the effective thickness of the epoxy (Section 3.1), reducing the modulus of the epoxy to 440 ksi (based on manufacturer's representation [48]) would only result in a potential increase in effective thickness. The computational assumptions of layered elastic analysis (see Chapter 2, Section 4) also contribute to the approximate nature of the calculation. Layered elastic analysis assumes that all pavement layers (including the epoxy layers above and below each core) extend laterally over the entire pavement section. The effect of this assumption should be minimal since the only calculated strains being evaluated are those actually above and below the layers of epoxy. Given these and other uncertainties in the measurement environment, it is believed that this difference in epoxy modulus is of minor concern. A summary of the layer characteristics used as input to CHEVPC is presented in Table 30.

Table 29. Summary of Calculated Depths to Stiff Layer Based on October 1991 WSDOT FWD Data—Axial Cores 1, 3, 4, and 5

Axial Core Number	Number of Drops at the Core	Average Depth to Stiff Layer ($\overline{X}$) (inches)	Standard Deviation (s) (inches)	Resulting Subgrade Thickness (inches)
1	10	61.1	1.2	42.7
3	5	64.4	1.1	46.0
4	2	64.5	1.9	46.1
5	4	62.2	1.8	43.8

Table 30. Summary of Layer Characteristics Used as Input to CHEVPC—October 1991 FWD Testing

Pavement Layer	Layer Modulus (psi)	Poisson's Ratio
Epoxy	500,000	0.35
AC	562,800	0.35
Base	14,800	0.40
Subgrade	10,200	0.45
Stiff Layer	40,000	0.35

3.3 Comparison of Measured and Calculated Strains

A comparative sample of the measured and calculated strains is shown in Table 31. Strains were measured at only three of the four gauges at each core. Due to the difficulty in matching the load data from each FWD drop to the corresponding measured strain data (these are two different data files from two different computer systems) the average load of all the same drop heights at each core was used to calculate the theoretical strain (descriptive statistics are contained in Table 32). A loss of measured strain data for Core 3 resulted in a comparison at drop height one only. As can be seen from the ratio of measured to calculated strains, the agreement is reasonable.

A more detailed analysis is provided in Figures 41-44. These figures plot the calculated versus measured strains for the axial core surface longitudinal, surface transverse, bottom longitudinal, and bottom transverse gauges, respectively. These plots indicate that, in general, the best agreement between measured and calculated strains is found with the longitudinal gauges (surface and bottom). The surface transverse gauges show the least satisfactory agreement (although acceptable). The descriptive statistics representing the measured to calculated ratio for each gauge category (top or bottom of AC, longitudinal or transverse orientation) are shown in Table 33. The dispersion about the mean is relatively consistent across gauge type. Since horizontal tensile strain at the bottom of the AC layer (as measured by the BL gauges) is a critical pavement response

Table 31. Comparison of Measured and Calculated Strains From 1991 FWD Testing—PACCAR Test Section

AXIAL CORE	GAUGE	DROP HEIGHT	AVERAGED LOAD	MICROSTRAIN MEASURED	MICROSTRAIN CALCULATED	RATIO (MEAS/CALC)
1	1BL*	1	5109	130	120	1.08
1	1BL*	2	10785	240	253	0.95
1	1BL	3	14196	324	333	0.97
1	1BT	1	5109	120	120	1.00
1	1BT	2	10785	267	253	1.06
1	1BT*	3	14196	383	333	1.15
1	3ST	1	5109	-108	-109	0.99
1	3ST	2	10785	-202	-231	0.87
1	3ST	3	14196	-222	-303	0.73
3	3BL	1	5110	76	76	1.00
3	7SL	1	5110	-118	-101	1.17
3	7ST	1	5110	-71	-101	0.70
4	10SL	1	5268	-148	-142	1.04
4	10SL	2	10849	-304	-293	1.04
4	10SL	3	14099	-449	-381	1.18
4	4BL	1	5268	125	125	1.00
4	4BL	2	10849	256	257	1.00
4	4BL	3	14099	381	334	1.14
4	4BT	1	5268	122	125	0.98
4	4BT	2	10849	249	257	0.97
4	4BT	3	14099	348	334	1.04
5	17SL	1	5204	-82	-95	0.86
5	17SL	2	10718	-172	-196	0.88
5	17SL	3	13479	-231	-246	0.94
5	5BL	1	5204	104	106	0.98
5	5BL	2	10718	226	217	1.04
5	5BL	3	13479	276	274	1.01
5	5BT	1	5204	86	106	0.81
5	5BT	2	10718	172	217	0.79
5	5BT	3	13479	224	274	0.82

* The measured strain was extrapolated from a plot of strain vs. time.

Mean	0.97
Standard Dev.	0.12
n	30

Table 32. Descriptive Statistics for FWD Loads—October 1991 FWD Testing

FWD LOAD (pounds)	Axial Core Number											
	Core 1			Core 3			Core 4			Core 5		
	Drop Height			Drop Height			Drop Height			Drop Height		
	1	2	3	1	2	3	1	2	3	1	2	3
Mean	5109	10785	14196	5110	10749	14021	5268	10849	14099	5204	10718	13479
Standard Deviation	58	42	49	110	70	93	N/A	N/A	N/A	N/A	N/A	73
Number of Drops	4	5	19	5	5	5	1	1	1	1	1	2

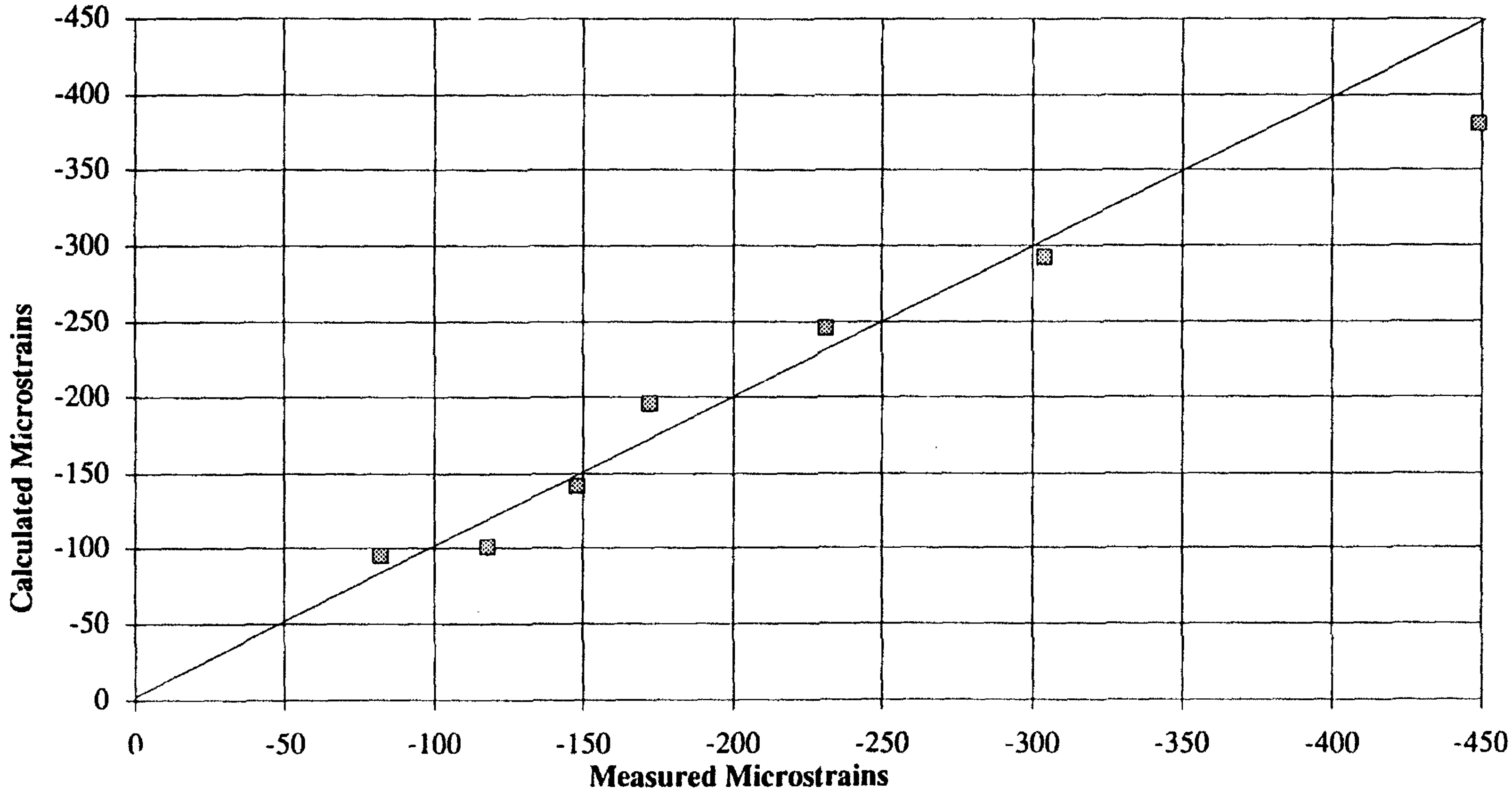


Figure 41. Measured vs. Calculated Strain For Axial Core Surface Longitudinal Gauges—October 1991 FWD Testing

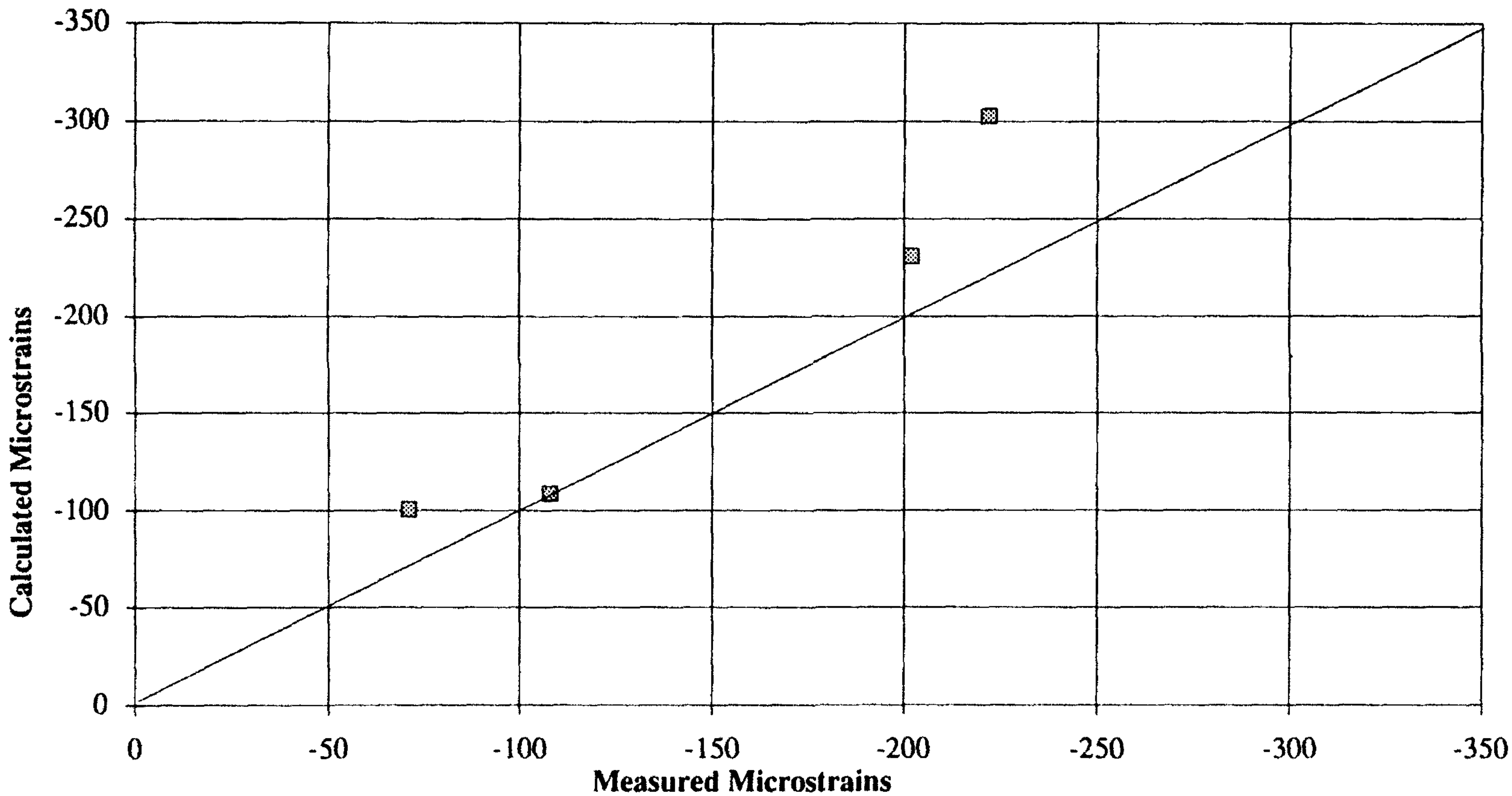


Figure 42. Measured vs. Calculated Strain For Axial Core Surface Transverse Gauges—October 1991 FWD Testing

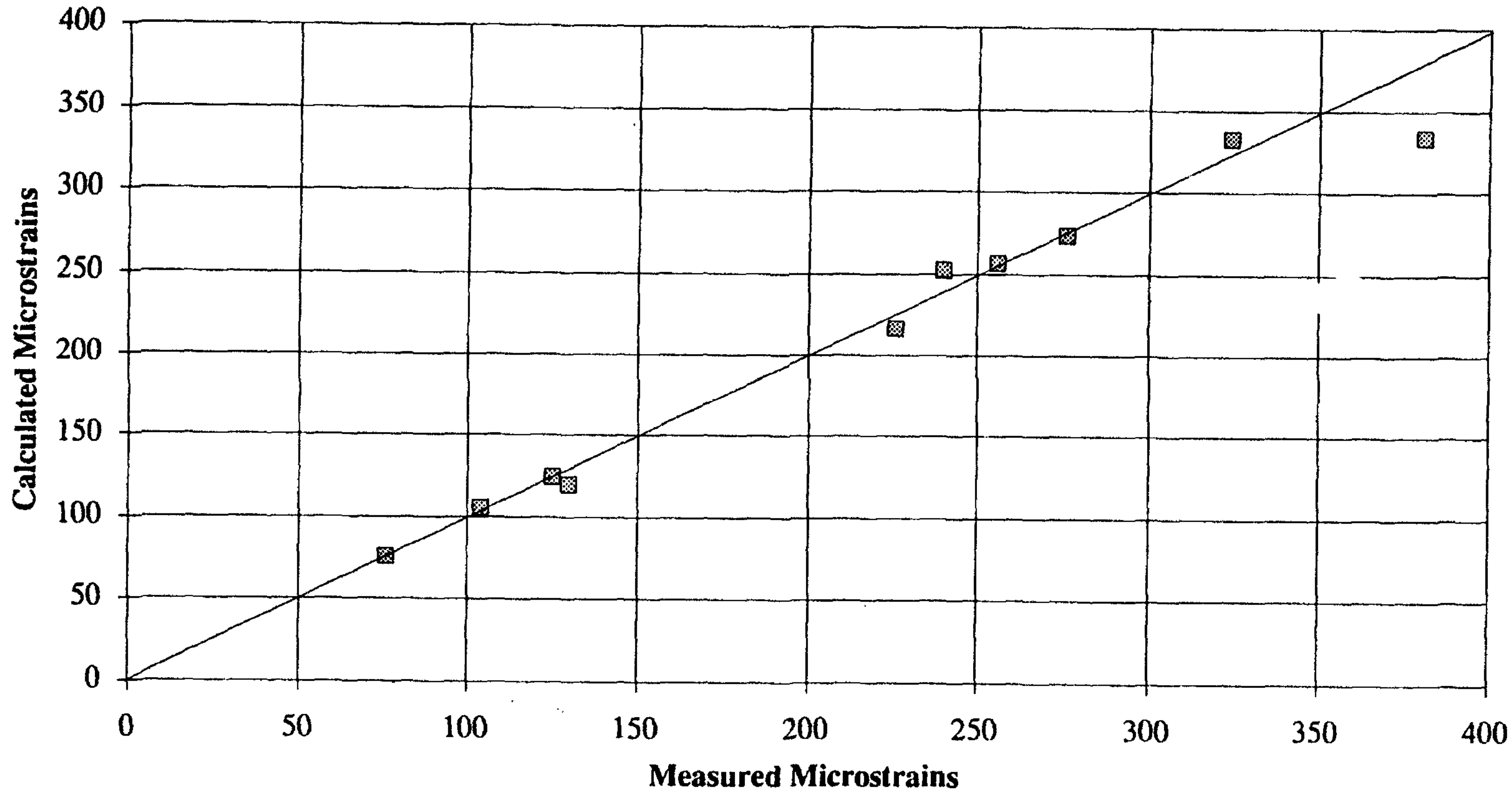


Figure 43. Measured vs. Calculated Strain For Axial Core Bottom Longitudinal Gauges—October 1991 FWD Testing

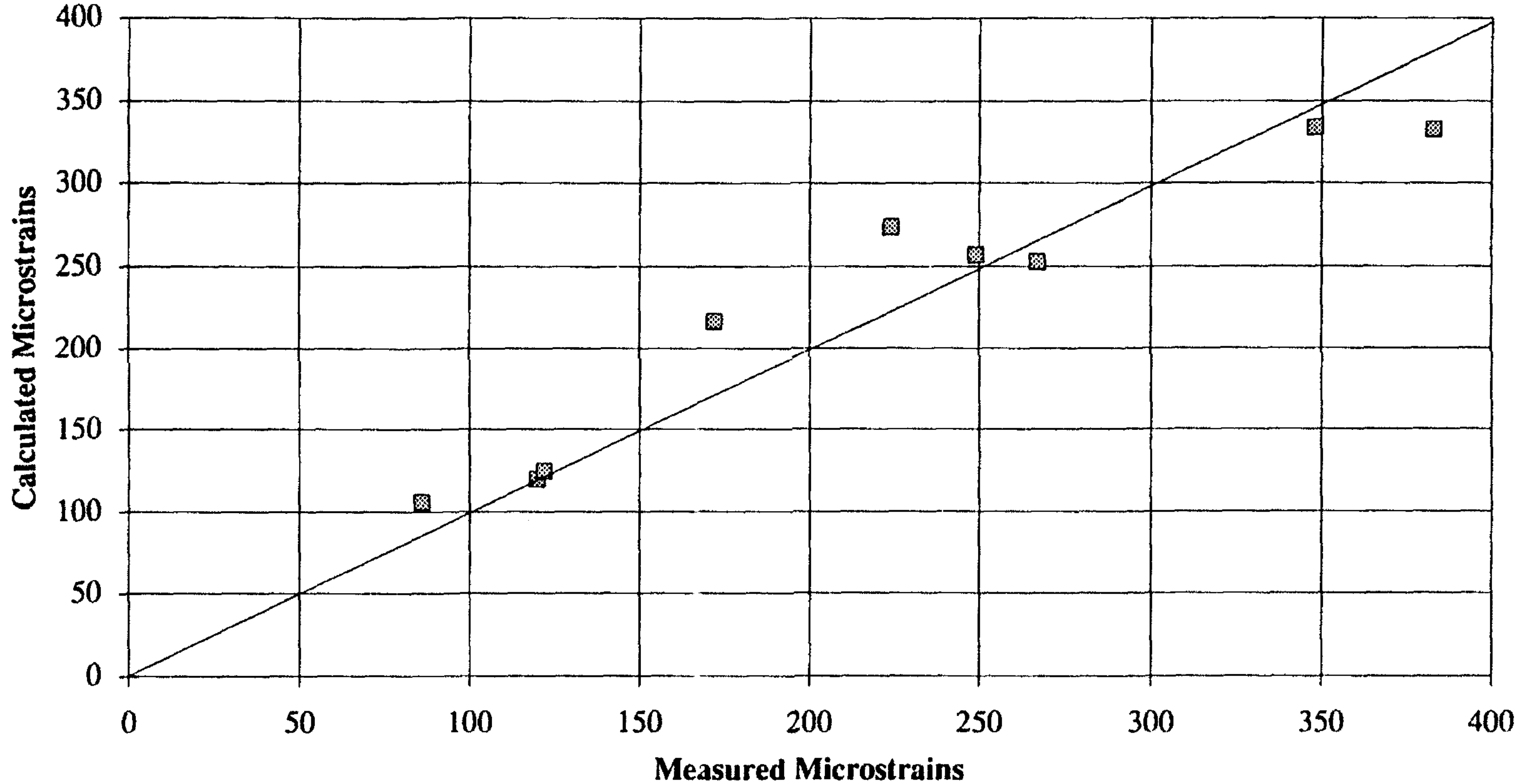


Figure 44. Measured vs. Calculated Strain For Axial Core Bottom Transverse Gauges—October 1991 FWD Testing

for mechanistic-empirical design, the performance of the BL gauge type is particularly noteworthy.

Measured to calculated ratios were also grouped for all gauges by drop height (Table 34) and core number (Table 35) for analysis. A review of these statistics shows relatively consistent performance across all drop heights and all cores.

4. FWD TESTING FEBRUARY 3, 1993

4.1 Backcalculation of Layer Moduli

The deflection data collected by the WSDOT FWD was used to backcalculate layer moduli using EVERCALC 3.3. This series of tests was only conducted over axial Cores 1, 3, 4, and 5. There were three drops at each of three drop heights (1, 2, and 4) per core. The intent was to backcalculate a set of layer moduli for each of the cores tested. Unfortunately, the deflection data for Cores 3 and 4 was lost due to a computer file problem. The resulting data base consisted of 18 deflection basins. To make maximum use of the measured strain data, the layer moduli backcalculated for Core 5 were used for analysis of Cores 3 and 4. The decision was based on the fact that Cores 3, 4, and 5 are on the same longitudinal line in the section (see Figure 33) and realistic moduli were calculated for the entire section from the October 1991 data based on a 61 location grid.

The applied load varied from 6050 to 17,880 pounds. Sensor spacings, layer thicknesses, and Poisson's ratios were the same as those used when backcalculating the October 1991 data (see Chapter 3, Section 3.1). The measured temperature of the AC layer at a depth of 2 inches was 46°F at the start of testing and 43°F at the conclusion of testing (air temperatures were 47°F and 44°F, respectively).

Initially, the stiff layer modulus was set at 40 ksi. The resulting layer moduli were unsatisfactory in that the AC and base moduli were too high and low, respectively (refer to Table 36.). A value of 50 ksi resulted in more realistic layer moduli with similar RMS error convergence. All the deflection basins (40 and 50 ksi stiff layer) resulted in

Table 33. Descriptive Statistics for Measured to Calculated Strain Ratios by Gauge Type—October 1991 FWD Testing

MEASURED TO CALCULATED RATIO	GAUGE TYPE			
	SL	ST	BL	BT
Mean	1.02	0.83	1.02	0.96
Standard Deviation	0.13	0.13	0.06	0.12
Minimum	0.86	0.70	0.95	0.79
Maximum	1.18	0.99	1.14	1.15
Sample Size	7	4	10	9

Table 34. Descriptive Statistics for Measured to Calculated Strain Ratios by Drop Height—October 1991 FWD Testing

MEASURED TO CALCULATED RATIO	FWD DROP HEIGHT		
	1 (5 ksi)	2 (10 ksi)	3 (14 ksi)
Mean	0.97	0.95	1.00
Standard Deviation	0.12	0.09	0.15
Minimum	0.70	0.79	0.73
Maximum	1.17	1.06	1.18
Sample Size	12	9	9

Table 35. Descriptive Statistics for Measured to Calculated Strain Ratios by Core—October 1991 FWD Testing

MEASURED TO CALCULATED RATIO	AXIAL CORE			
	Core 1	Core 3	Core 4	Core 5
Mean	0.98	0.96	1.04	0.90
Standard Deviation	0.12	0.24	0.07	0.09
Minimum	0.73	0.7	0.97	0.79
Maximum	1.15	1.17	1.18	1.04
Sample Size	9*	3**	9*	9*

Notes:

* Based on 3 drops at 3 gauges.

** Based on 1 drop at 3 gauges.

an RMS error convergence of 1.7 percent or less. The mean values for the AC modulus were 1,575 ksi for Core 1 and 1,510 ksi for Core 5. This is remarkably close to the laboratory value of 1,490 ksi for Class B ACP at 45° F (see Figure 27). A summary of the resulting layer moduli and RMS statistics is shown in Tables 36-38.

4.2 Effective Layer Thicknesses

The only layer thicknesses that were changed for analysis of this data were the subgrade thicknesses. The subgrade thickness was determined by evaluating the calculated depth to stiff layer in the same manner as was done for the October 1991 data. Since there was no available information to determine the subgrade thickness for Cores 3 and 4, and the difference between the calculated depth for Cores 1 and 5 was generally the same for both testing periods (1.1 inches in October; 1.3 inches in February), the subgrade thicknesses for Cores 3 and 4 were based on this same relationship. A summary of the stiff layer depths (and resulting subgrade thicknesses) is contained in Table 39. It is interesting to note that the calculated depth to stiff layer is about 14 inches deeper in February 1993 than calculated in October 1991 (as calculated by EVERCALC). This is indirectly supported by the fact that rainfall in the 13 months preceding the February testing was approximately 7 inches below normal. [50]

The epoxy thicknesses were not changed for two reasons. First, it was felt that the data collected in October 1991 matched the in situ relationship between gauge, epoxy, and AC more closely - at least chronologically. Second, this allows for a more direct comparison between the two tests.

4.3 Calculated Strains

The theoretical strains were calculated using the same procedure as for the October 1991 data. Table 40 summarizes the layer characteristics used as input to CHEVPC. The stiff layer modulus of 50 ksi was used due to the resulting AC modulus, even though the RMS error was slightly larger (0.1 percent).

Table 36. Sensitivity of Layer Moduli as a Function of the Stiff Layer Modulus — PACCAR Test Section, February 1993 FWD Testing

PAVEMENT LAYERS	E_{stiff}			
	Core 1		Core 5	
	40 ksi	50 ksi	40 ksi	50 ksi
Asphalt Concrete* (ksi)	1,874	1,576	1,949	1,510
Crushed Stone Base* (ksi)	11	20	13	27
Fine-grained Subgrade* (ksi)	14	11	18	13

*All runs resulted in a RMS% <=1.7%.

Table 37. Sensitivity of RMS Values as a Function of the Stiff Layer Modulus — PACCAR Test Section, February 1993 FWD Testing

RMS (%)	E_{stiff}	
	40 ksi	50 ksi
Mean*	1.1	1.2
Standard Deviation*	0.3	0.3
Minimum*	0.6	0.7
Maximum*	1.5	1.7
Total Runs with RMS% <=1.7*	18	18

*Calculated for 18 deflection basins.

Table 38. Descriptive Statistics for Backcalculated Layer Moduli—February 1993 FWD Testing

PAVEMENT LAYER MODULI (psi)	AXIAL CORE NUMBER					
	Core 1			Core 5		
	AC	Base	Subgrade	AC	Base	Subgrade
Mean	1,575,700	20,300	10,700	1,510,300	27,500	13,400
Standard Deviation	197,300	4,000	400	128,600	1,800	501
Minimum	1,351,800	14,800	10,200	1,339,500	24,900	12,601
Maximum	1,832,300	25,600	11,000	1,679,000	30,200	13,742
Number of Drops	9	9	9	9	9	9

Note:
Stiff Layer Modulus set at 50 ksi.

Table 39. Summary of Calculated Depths to Stiff Layer Based on February 1993 FWD Data - Axial Cores 1, 3, 4, and 5

Axial Core Number	Depth to Stiff Layer ($\bar{X}$) (inches)	Resulting Subgrade Thickness (inches)
1	75.5	57.1
3	78.8*	60.4
4	78.9*	60.5
5	76.8	58.4

* Based on relationship established between Cores 1 and 5 from October 1991 FWD Data.

Table 40. Summary of Layer Characteristics Used as Input to CHEVPC—February 1993 FWD Testing

	Core 1		Cores 3, 4, and 5	
PAVEMENT LAYER	Layer Modulus (psi)	Poisson's Ratio	Layer Modulus (psi)	Poisson's Ratio
Epoxy	500,000	0.35	500,000	0.35
AC	1,575,700	0.35	1,510,300	0.35
Base	20,300	0.40	27,500	0.40
Subgrade	10,700	0.45	13,400	0.45
Stiff Layer	50,000	0.35	50,000	0.35

4.4 Comparison of Measured and Calculated Strains

In this test series, strains were measured at all four gauges at each core. The averaged FWD loads for each drop height at each core were used for Cores 1 and 5. Since this data was missing for Cores 3 and 4, the average of the loads used for Cores 1 and 5 was used for Cores 3 and 4 (descriptive statistics are contained in Table 41). A comparison of the measured and calculated strains is shown in Table 42. With a few exceptions, the agreement is within reasonable limits.

A plot of the calculated versus measured strain for the surface longitudinal, surface transverse, bottom longitudinal, and bottom transverse gauges is contained in Figures 45-48, respectively. In general, the best agreement is found with the bottom gauges (longitudinal and transverse). The descriptive statistics representing the measured to calculated ratio for each gauge type are shown in Table 43. Dispersion about the mean is generally consistent excluding the BT gauges which show more variability. The agreement between measured and calculated strains is acceptable for all gauge types except the ST gauges. While the standard deviation is modest, the mean value is too low. A possible explanation for this poor agreement is the misalignment of the FWD load plate over the cores. If the load plate was not centered over the cores one would expect the effect of this misalignment to dissipate with depth. In fact, the mean value of the measured to calculated ratio for both surface gauges is substantially lower than that of the bottom gauges.

Table 44 shows relatively consistent agreement across all three drop heights. When the measured to calculated ratios are compared across cores (Table 45), Core 4 indicates poor agreement. The reason for this is unknown. It is unlikely that any of the assumptions made regarding depth to stiff layer or layer moduli could have affected the agreement. The assumptions appear reasonable for Core 3, and Cores 3 and 4 are only two feet apart.

Table 41. Descriptive Statistics for FWD Loads—February 1993 FWD Testing

FWD LOAD (pounds)	Axial Core Number								
	Core 1			Cores 3 and 4*			Core 5		
	Drop Height			Drop Height			Drop Height		
	1	2	4	1	2	4	1	2	4
Mean	6205	10,753	17,614	6160	10,660	17,730	6114	10,563	17,853
Standard Deviation	151	98	20	115	127	134	62	61	36
Number of Drops	3	3	3	6	6	6	3	3	3

Note:

* Calculated from loads at Cores 1 and 5.

Table 42. Comparison of Measured and Calculated Strains from February 1993 WSDOT FWD Testing - PACCAR Test Section

CORE	GAUGE	DROP HEIGHT	AVERAGED LOAD	MICROSTRAIN		RATIO (MEAS/CALC)
				MEASURED	CALCULATED	
1	1BL	1	6205	71	79	0.90
1	1BL	2	10753	99	138	0.72
1	1BL	4	17614	171	226	0.76
1	1BT	1	6205	91	79	1.15
1	1BT	2	10753	162	138	1.17
1	1BT	4	17614	253	226	1.12
1	3SL	1	6205	-46	-73	0.63
1	3SL	2	10753	-81	-126	0.64
1	3SL	4	17614	-122	-208	0.59
1	3ST	1	6205	-62	-73	0.85
1	3ST	2	10753	-100	-126	0.79
1	3ST	4	17614	-153	-208	0.74
3	3BL	1	6160	68	60	1.13
3	3BL	2	10660	125	105	1.19
3	3BL	4	17730	205	175	1.17
3	3BT	1	6160	70	60	1.17
3	3BT	2	10660	131	105	1.25
3	3BT	4	17730	212	175	1.21
3	7SL	1	6160	-63	-66	0.95
3	7SL	2	10660	-90	-114	0.79
3	7SL	4	17730	-164	-190	0.86
3	7ST	1	6160	-35	-66	0.53
3	7ST	2	10660	-44	-114	0.39
3	7ST	4	17730	-85	-190	0.45

Table 42. Comparison of Measured and Calculated Strains from February 1993 WSDOT FWD Testing - PACCAR Test Section (continued)

CORE	GAUGE	DROP HEIGHT	AVERAGED LOAD	MICROSTRAIN		RATIO (MEAS/CALC)
				MEASURED	CALCULATED	
4	4BL	1	6160	70	76	0.92
4	4BL	2	10660	113	131	0.86
4	4BL	4	17730	178	218	0.82
4	4BT	1	6160	61	76	0.80
4	4BT	2	10660	106	131	0.81
4	4BT	4	17730	151	218	0.69
4	10SL	1	6160	-53	-77	0.69
4	10SL	2	10660	-97	-133	0.73
4	10SL	4	17730	-155	-221	0.70
4	8ST	1	6160	-49	-77	0.64
4	8ST	2	10660	-99	-133	0.74
4	8ST	4	17730	-153	-221	0.69
5	5BL	1	6114	89	69	1.29
5	5BL	2	10563	114	119	0.96
5	5BL	4	17853	188	200	0.94
5	5BT	1	6114	119	69	1.72
5	5BT	2	10563	156	119	1.31
5	5BT	4	17853	233	200	1.17
5	17SL	1	6114	-54	-62	0.87
5	17SL	2	10563	-120	-107	1.12
5	17SL	4	17853	-164	-181	0.91
5	9ST	1	6114	-44	-62	0.71
5	9ST	2	10563	-98	-107	0.92
5	9ST	4	17853	-145	-181	0.80
					Mean	0.90
					Standard Dev.	0.26
					n	48

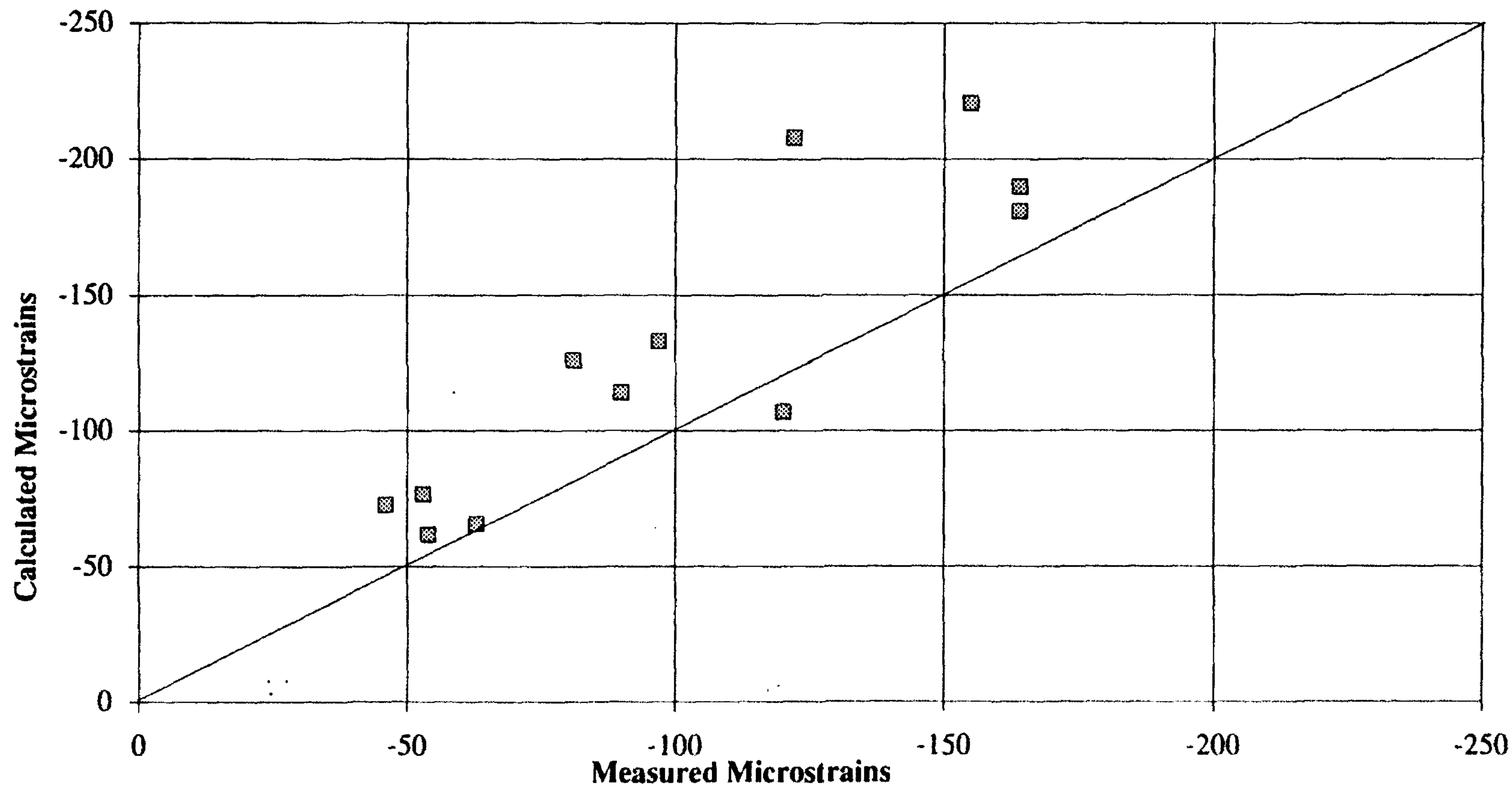


Figure 45. Measured vs. Calculated Strain For Axial Core Surface Longitudinal Gauges—February 1993 FWD Testing

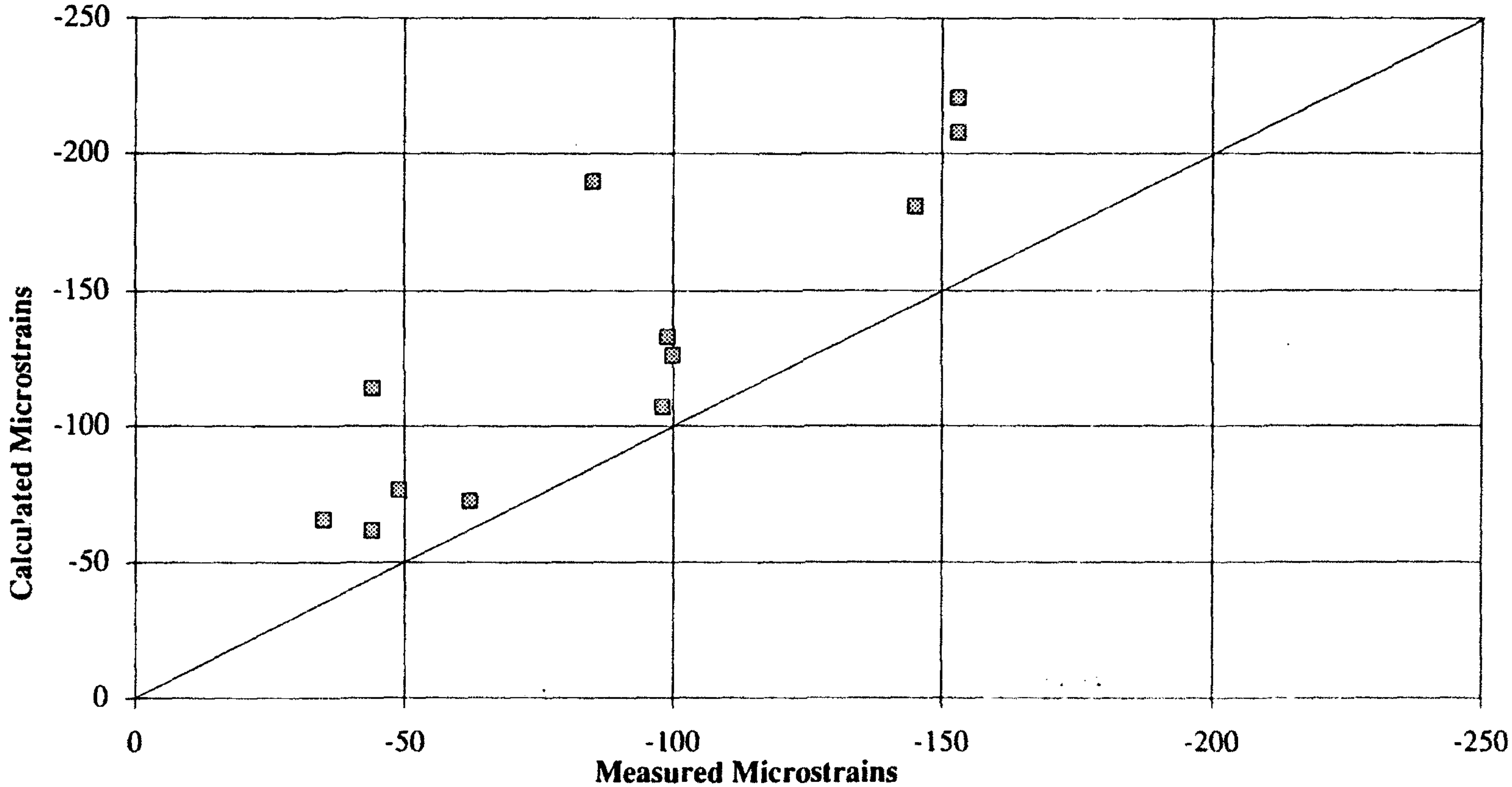


Figure 46. Measured vs. Calculated Strain For Axial Core Surface Transverse Gauges—February 1993 FWD Testing

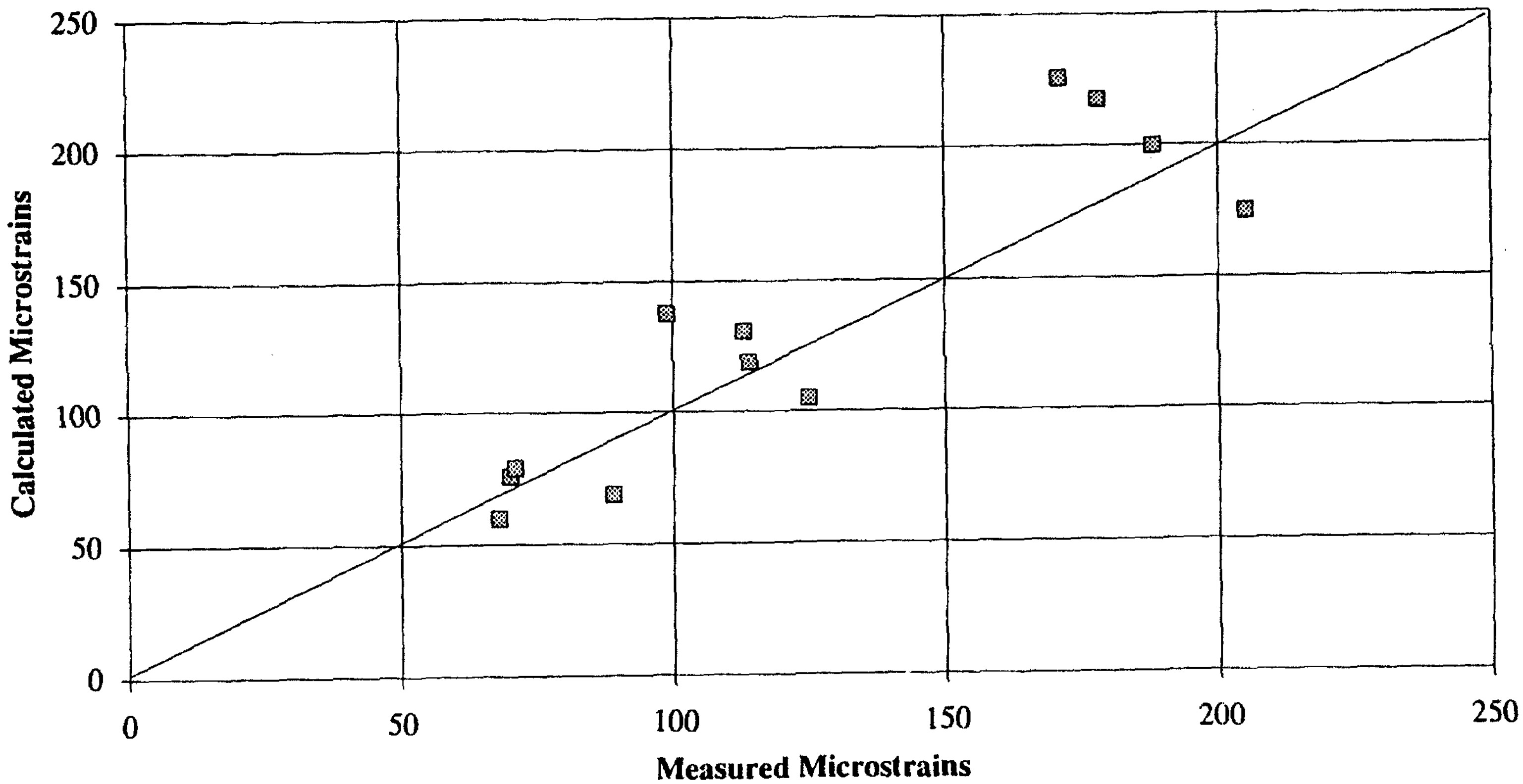


Figure 47. Measured vs. Calculated Strain For Axial Core Bottom Longitudinal Gauges—February 1993 FWD Testing

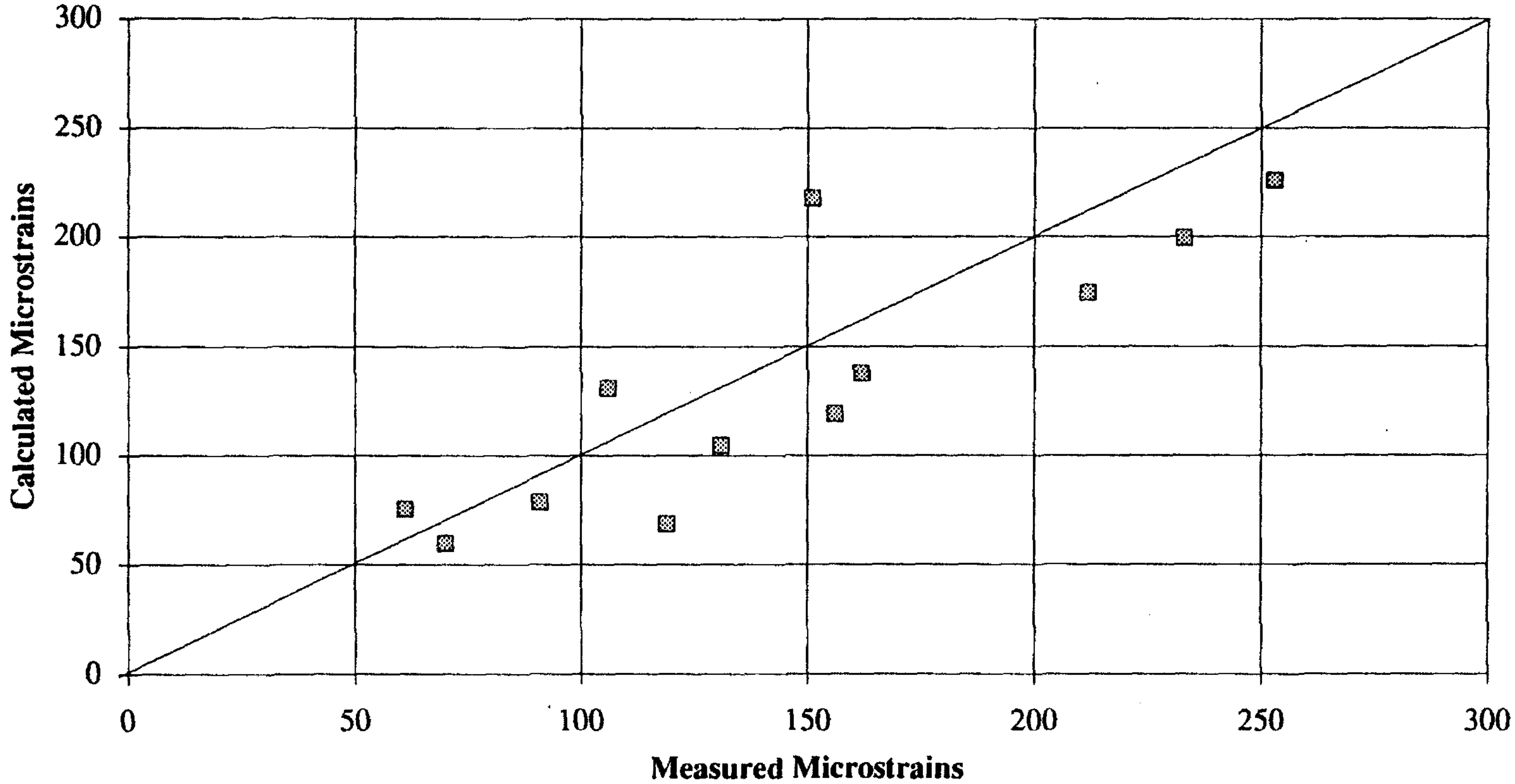


Figure 48. Measured vs. Calculated Strain For Axial Core Bottom Transverse Gauges—February 1993 FWD Testing

Table 43. Descriptive Statistics for Measured to Calculated Strain Ratios by Gauge Type—February 1993 FWD Testing

MEASURED TO CALCULATED RATIO	GAUGE TYPE			
	SL	ST	BL	BT
Mean	0.79	0.69	0.97	1.13
Standard Deviation	0.16	0.16	0.18	0.27
Minimum	0.59	0.39	0.72	0.69
Maximum	1.12	0.92	1.29	1.72
Sample Size	12	12	12	12

Table 44. Descriptive Statistics for Measured to Calculated Strain Ratios by Drop Height—February 1993 FWD Testing

MEASURED TO CALCULATED RATIO	FWD DROP HEIGHT		
	1 (5 ksi)	2 (10 ksi)	4 (17 ksi)
Mean	0.93	0.90	0.85
Standard Deviation	0.30	0.25	0.22
Minimum	0.53	0.39	0.45
Maximum	1.72	1.31	1.21
Sample Size	16	16	16

Table 45. Descriptive Statistics for Measured to Calculated Strain Ratios by Core—February 1993 FWD Testing

MEASURED TO CALCULATED RATIO	AXIAL CORE			
	Core 1	Core 3	Core 4	Core 5
Mean	0.84	0.92	0.76	1.06
Standard Deviation	0.21	0.32	0.08	0.28
Minimum	0.59	0.39	0.64	0.71
Maximum	1.17	1.25	0.92	1.72
Sample Size*	12	12	12	12

* Based on 3 drops at 4 gauges.

5. COMPARISON OF OCTOBER 1991 AND FEBRUARY 1993 FWD TESTING

Given the variability of the testing conditions, it is difficult to perform any definitive comparisons between the two FWD tests. Furthermore, making such comparisons is not the primary purpose of the test section. However, at least two positive observations are appropriate.

First, the BL gauges have shown the best agreement between measured and calculated strains for both test series. Given the importance of this pavement response parameter to mechanistic analyses, the impact of this observation is significant. Second, the strain gauges have shown no sensitivity to load magnitude. Since future testing at this track will examine the effect of varying loads and tire pressures on pavement response, this condition is also critical.

The least satisfactory agreement between measured and calculated strains was observed for the ST gauges. While this is unfortunate, the response measured by these gauges is the least important for this section.

A comparison of the measured to calculated strain ratios for the October 1991 and February 1993 FWD testing is shown in Table 46. While there is moderate variability between the two tests, the mean value for the October 1991 to February 1993 ratio is 1.10. The amount of variability is not surprising given the uncertainty in alignment of the FWD load plate over the cores.

In an attempt to evaluate individual gauge performance, the mean value of the measured to calculated ratio was calculated for each gauge that was monitored during both the October and February FWD tests. The results are shown in Table 47. All but three gauges show relatively consistent performance. Gauges 10SL and 5BT have a reasonable measured to calculated ratio (mean value) but unusually high standard deviations. Once again, FWD alignment over the core is a potential source of this dispersion. The measured to calculated ratio for 7ST is substantially lower than all other gauges.

Table 46. Comparison of Measured to Calculated Strain Ratios from February 1993 and October 1991 FWD Testing - PACCAR Test Section

CORE	GAUGE	DROP HEIGHT	MEAS/CALC RATIO Oct-91	MEAS/CALC RATIO Feb-93	RATIO (OCT/FEB)
1	1BL	1	1.08	0.90	1.20
1	1BL	2	0.95	0.72	1.32
1	1BL	3 or 4	0.97	0.76	1.28
1	1BT	1	1.00	1.15	0.87
1	1BT	2	1.06	1.17	0.90
1	1BT	3 or 4	1.15	1.12	1.03
1	3ST	1	0.99	0.85	1.16
1	3ST	2	0.87	0.79	1.10
1	3ST	3 or 4	0.73	0.74	0.99
3	3BL	1	1.00	1.13	0.88
3	7SL	1	1.17	0.95	1.23
3	7ST	1	0.70	0.53	1.32
4	4BL	1	1.00	0.92	1.09
4	4BL	2	1.00	0.86	1.16
4	4BL	3 or 4	1.14	0.82	1.39
4	4BT	1	0.98	0.80	1.23
4	4BT	2	0.97	0.81	1.20
4	4BT	3 or 4	1.04	0.69	1.51
4	10SL	1	1.04	0.69	1.51
4	10SL	2	1.04	0.73	1.42
4	10SL	3 or 4	1.18	0.70	1.69
5	5BL	1	0.98	1.29	0.76
5	5BL	2	1.04	0.96	1.08
5	5BL	3 or 4	1.01	0.94	1.07
5	5BT	1	0.81	1.72	0.47
5	5BT	2	0.79	1.31	0.60
5	5BT	3 or 4	0.82	1.17	0.70
5	17SL	1	0.86	0.87	0.99
5	17SL	2	0.88	1.12	0.79
5	17SL	3 or 4	0.94	0.91	1.04

Mean	1.10
Standard Dev.	0.28
n	30

Table 47. Descriptive Statistics for Measured to Calculated Ratios for Selected Gauges—October 1991 and February 1993 FWD Testing

Gauge Designation	Mean	Standard Deviation	n
1BL	0.90	0.14	6
1BT	1.11	0.07	6
3ST	0.83	0.10	5
3BL	1.12	0.09	4
7SL	0.94	0.17	4
7ST	0.52	0.13	4
4BL	0.96	0.12	6
4BT	0.88	0.14	6
10SL	0.90	0.21	6
5BL	1.04	0.13	6
5BT	1.10	0.37	6
17SL	0.93	0.10	6

6. COMPARISON OF MEASURED LONGITUDINAL AND TRANSVERSE STRAINS

A comparison of the longitudinal and transverse strain measured at the surface and bottom of each core and FWD drop height during the February 1993 FWD testing is shown in Figures 49 and 50. As was observed by other researchers [28, 37], measured longitudinal and transverse strains due to FWD and tire loads were not equal for any given measurement location.

In general, longitudinal strain measured at the pavement surface (Figure 49) is larger than the transverse strain (3 of the 4 cores). However, at Core 1 the transverse strain is larger. The two strains are close to being equal at Core 4. At the bottom of the AC, the dominant strain seems to reverse (Figure 50). In general, transverse strain is larger (3 of 4 cores) at this pavement location. The longitudinal strain measured at Core 4 is larger and the two strains are closest in magnitude at Core 3. There is no obvious explanation for these differences. As previously mentioned, FWD alignment could have some influence. Unfortunately, a similar comparison of the October 1991 data can not be performed due to a lack of surface strain measurements.

7. OTHER TESTING

A series of full scale truck tests was conducted on May 1 and 4, 1992, to provide an initial evaluation of strain gauge performance over varying tire pressures and truck speeds. A comparison of the measured and calculated strains from 50 gauge responses is shown in Table 48. The average measured to calculated ratio for all runs is 0.60. The strains measured at 4 mph more closely resemble the static analysis of dynamic data conducted with the October 1991 and February 1993 FWD data. The comparison of measured to calculated strains should deviate with increasing speed due to this computational limitation. The average ratio for the measured and calculated strains from the 27 gauge responses at 4 mph is 0.57.

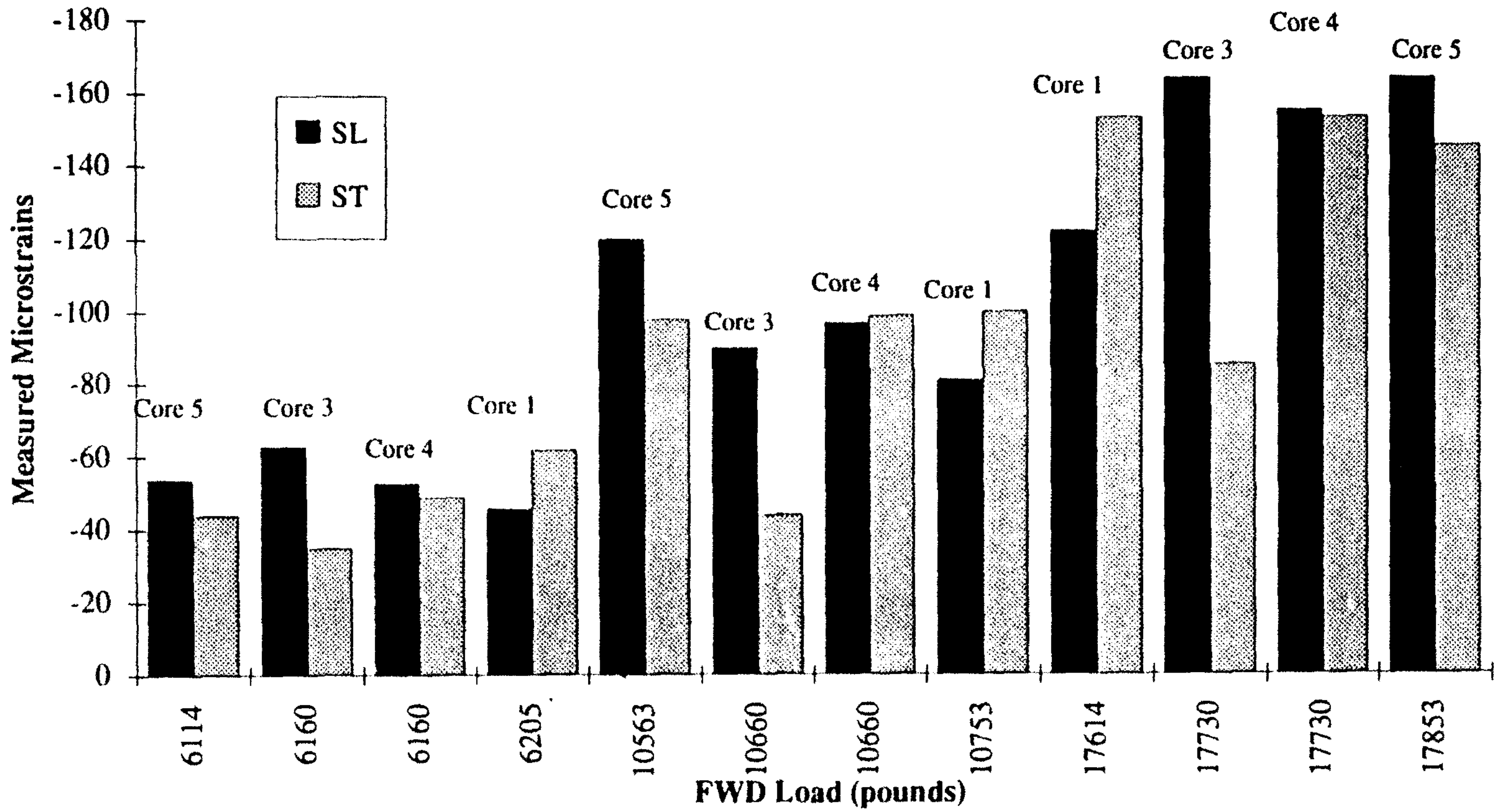


Figure 49. Comparison of Measured Longitudinal and Transverse Strain at the AC Surface—February 1993 FWD Testing

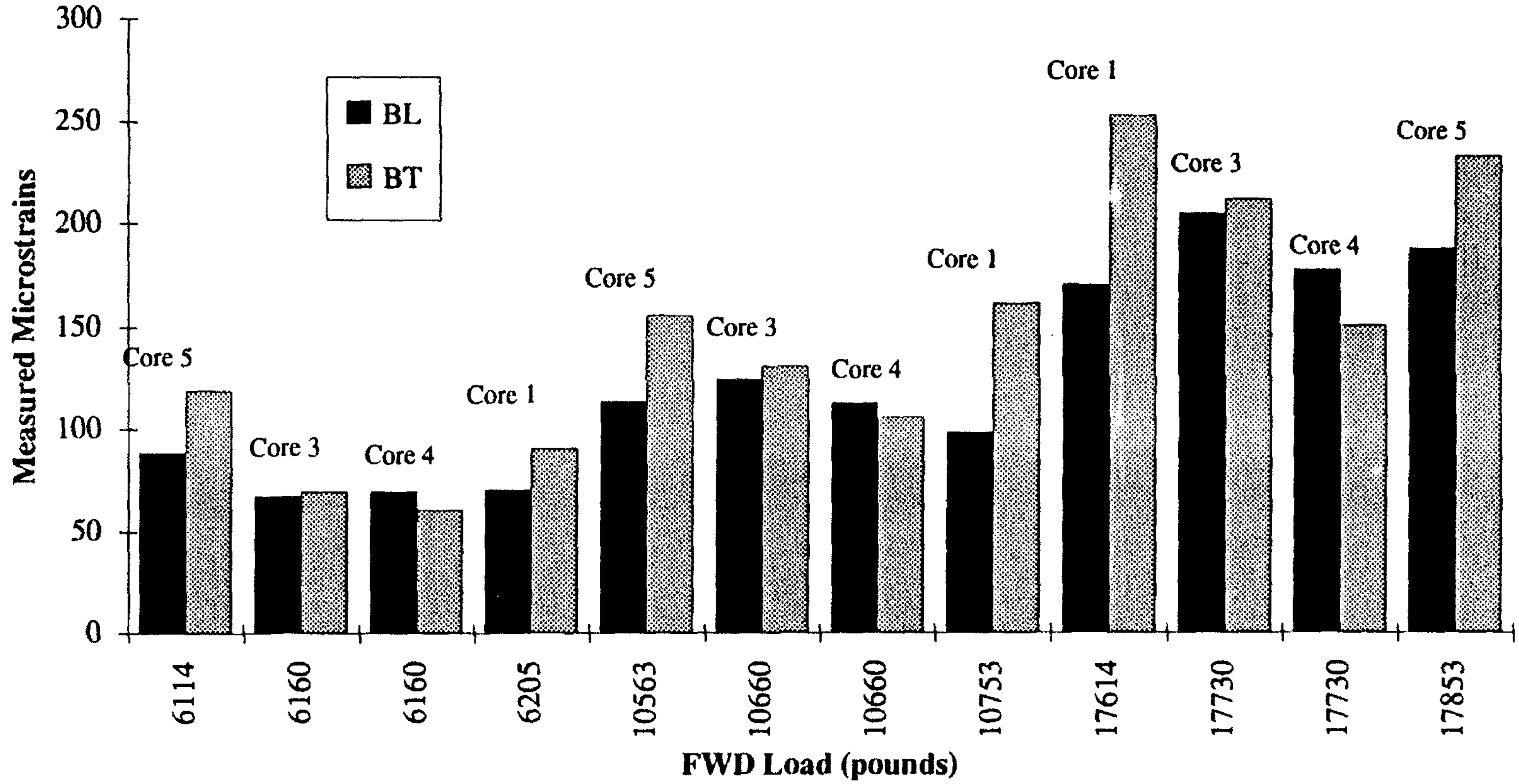


Figure 50. Comparison of Measured Longitudinal and Transverse Strain at the Bottom of the AC—February 1993 FWD Testing

Table 48. Comparison of Measured and Calculated Strains from May 1992 Truck Testing—PACCAR Test Section

RUN	CORE	GAUGE	TIRE LOAD	PSI	SPEED MPH	MICROSTRAIN		RATIO (MEAS/CALC)
						MEASURED	CALCULATED	
10	1	1BL	5530	45	4	138	124	1.11
14	1	1BL	5530	45	20	130	124	1.05
18	1	1BL	5530	45	40	105	124	0.85
2	1	1BL	5530	100	4	135	167	0.81
5	1	1BL	5530	100	20	107	167	0.64
8	1	1BL	5530	100	40	82	167	0.49
11	1	3SL*	5530	45	4	-95	-117	0.81
11	1	3ST	5530	45	4	-72	-117	0.62
10	3	3BL	6070	45	4	59	78	0.76
11	3	3BL	6070	45	4	60	78	0.77
14	3	3BL	6070	45	20	65	78	0.83
18	3	3BL	6070	45	40	66	78	0.85
2	3	3BL	6070	100	4	70	105	0.67
5	3	3BL	6070	100	20	56	105	0.53
8	3	3BL	6070	100	40	51	105	0.49
10	3	3BT	6070	45	4	29	78	0.37
11	3	3BT	6070	45	4	55	78	0.71
14	3	3BT	6070	45	20	70	78	0.90
18	3	3BT	6070	45	40	89	78	1.14
2	3	3BT	6070	100	4	68	105	0.65
5	3	3BT	6070	100	20	52	105	0.50
8	3	3BT	6070	100	40	72	105	0.69
1	3	7SL	6070	100	4	-55	-150	0.37
11	3	7SL*	6070	45	4	-50	-117	0.43
11	3	7ST*	6070	45	4	-90	-117	0.77
1	3	7ST*	6070	100	4	-35	-150	0.23
3	3	7ST*	6070	100	4	-70	-150	0.47

Table 48. Comparison of Measured and Calculated Strains from May 1992 Truck Testing—PACCAR Test Section (continued)

RUN	CORE	GAUGE	TIRE LOAD	PSI	SPEED MPH	MICROSTRAIN MEASURED	MICROSTRAIN CALCULATED	RATIO (MEAS/CALC)
10	4	4BL	6070	45	4	53	129	0.41
11	4	4BL	6070	45	4	65	129	0.50
14	4	4BL	6070	45	20	60	129	0.47
18	4	4BL	6070	45	40	60	129	0.47
2	4	4BL	6070	100	4	70	179	0.39
5	4	4BL	6070	100	20	54	179	0.30
8	4	4BL	6070	100	40	60	179	0.34
11	4	8ST*	6070	45	4	-80	-161	0.50
1	4	8ST*	6070	100	4	-50	-215	0.23
3	4	8ST*	6070	100	4	-110	-215	0.51
11	5	17SL*	6070	45	4	-70	-106	0.66
10	5	5BL	6070	45	4	65	112	0.58
14	5	5BL	6070	45	20	70	112	0.63
18	5	5BL	6070	45	40	87	112	0.78
2	5	5BL	6070	100	4	75	150	0.50
5	5	5BL	6070	100	20	56	150	0.37
8	5	5BL	6070	100	40	70	150	0.47
10	5	5BT	6070	45	4	35	112	0.31
14	5	5BT	6070	45	20	72	112	0.64
18	5	5BT	6070	45	40	109	112	0.97
2	5	5BT	6070	100	4	70	150	0.47
5	5	5BT	6070	100	20	50	150	0.33
8	5	5BT	6070	100	40	76	150	0.51
11	5	9ST*	6070	45	4	-80	-106	0.75

* The strain-time plot did not follow the same general pattern as seen for other gauges at the same location and measuring in the same direction.

It is important to reiterate the observation made by Scazziga et al. [35] regarding transverse vehicle alignment over strain gauge locations (see Chapter 2, Section 7.2). Misalignment of 2 inches resulted in a 50 percent reduction in strain calculated at the bottom of the AC layer. Since alignment accuracy during the May truck testing was not measured it is certainly a possible contributor to the poor agreement found from this testing.

FWD testing was conducted over axial Cores 3 and 4 on June 15, 1992. The measured and calculated strains from this testing are shown in Table 49. The average measured to calculated strain ratio is 0.74 with a standard deviation of 0.46. The testing conditions were surprisingly similar to those of the October 1991 FWD testing. The AC temperature was only 3° F higher (71° F vs. 68° F) in June. EVERCALC calculated a stiff layer at the same depth for Core 4 and only 0.8 of an inch deeper for Core 3. Additionally, all the deflection basins resulted in an average RMS error convergence of 1.3 percent after backcalculation. A plot of the deflection at the center of the load plate versus FWD load for both FWD tests (October 1991 and June 1992) is shown in Figure 51. In general, the agreement between the two tests is very close with somewhat more dispersion in the June data.

The reasons for the relatively poor agreement seen in these two test series are unknown. On the basis of the discussion above, it is unlikely that FWD variability contributed to this poor agreement. It is unclear if the signal conditioning, system calibration, or data collection affected the agreement.

Table 49. Comparison of Measured and Calculated Strains from June 1992 WSDOT FWD Testing - PACCAR Test Section

CORE	GAUGE	DROP HEIGHT	AVERAGED LOAD	MICROSTRAIN		RATIO (MEAS/CALC)
				MEASURED	CALCULATED	
3	7ST	1	5313	-50	-111	0.45
3	7ST	2	9493	-105	-198	0.53
3	7ST	3	10946	-131	-228	0.57
3	3BL	1	5313	125	75	1.67
3	3BL	2	9493	223	133	1.68
3	3BL	3	10946	250	154	1.62
3	3BT	1	5313	78	75	1.04
3	3BT	2	9493	151	133	1.14
3	3BT	3	10946	175	154	1.14
4	8ST	1	5313	-44	-155	0.28
4	8ST	2	9493	-84	-275	0.31
4	8ST	3	10946	-100	-318	0.31
4	10SL	1	5313	-81	-155	0.52
4	10SL	2	9493	-153	-275	0.56
4	10SL	3	10946	-181	-318	0.57
4	4BL	1	5313	75	126	0.60
4	4BL	2	9493	144	223	0.65
4	4BL	3	10946	169	259	0.65
4	4BT	1	5313	48	126	0.38
4	4BT	2	9493	94	223	0.42
4	4BT	3	10946	106	259	0.41

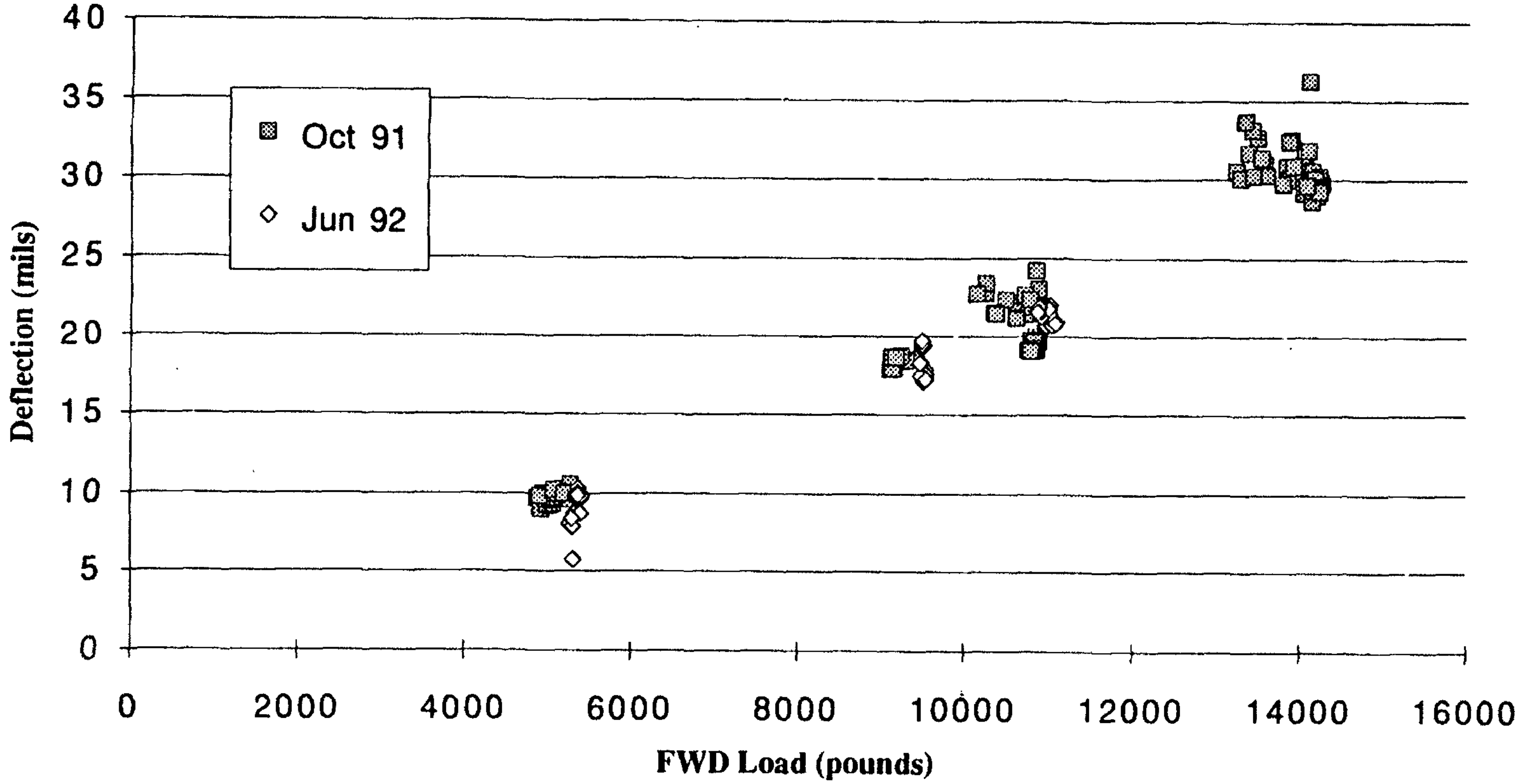


Figure 51. Deflection at the Center of the FWD Load Plate vs. FWD Load—
October 1991 and June 1992 FWD Testing

CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. SUMMARY

A full-scale, instrumented, flexible pavement section was designed and constructed at the PACCAR Technical Center. FWD testing was conducted to characterize the layer properties of the pavement section and compare the strains measured under the FWD load to those calculated using layer elastic analysis.

A review of the available literature has shown that reasonable agreement between measured and calculated strains in AC layers can be expected under a wide variety of experimental conditions. These conditions include pavement structure, source and magnitude of load, strain measurement technique, and source of theoretical computation. The results of the majority of the previous experiments support the conclusion drawn by Scazziga et al. [35] and the OECD Scientific Expert Group [38] that a range of ± 20 percent represents reasonable agreement between measured and calculated strains.

From backcalculated layer moduli for the PACCAR section, it was found that the saturated condition of the subgrade triggered the stiff layer algorithm in EVERCALC 3.3. Further, a stiff layer modulus of 40 or 50 ksi (instead of the traditional value of 1000 ksi) resulted in more realistic layer moduli for the other pavement layers. This has been true over three series of FWD tests during three seasons (Fall, Summer, and Winter). Standing water year round just 50 feet from the section also supports this observation. Analysis of two locations on SR525 yielded similar results.

Analysis of the strains under FWD loading conducted on October 10, 1991 has shown that 90 percent of the measured strains are within ± 20 percent of their calculated values. Fifty percent of the strains measured during the FWD testing conducted on February 3, 1993 were within ± 20 percent of calculated. The gauges measuring horizontal tensile strain at the bottom of the AC have shown the best agreement with theoretical strains calculated using CHEVPC. Strains measured during FWD and truck testing on June 15, 1992 and May 1, 1992, respectively, resulted in reduced agreement between measured and calculated strains. While the reasons for this poor agreement are unknown, it is speculated that the uncertainty of wheel alignment over the cores (gauges) is a major factor in the May truck testing. Relatively small variations in wheel alignment over a strain gauge have been shown to have a major influence on calculated strain responses measured by gauges mounted at the surface and bottom of the AC layer. [35]

The magnitude of longitudinal and transverse strains measured at any given gauge location is unequal. At the surface of the AC, the longitudinal strain is generally larger than the transverse strain, although not always. At the bottom of the AC, the transverse strain becomes larger in most cases. While it can not be supported by empirical evidence, it is suggested that misalignment of the FWD load plate over the gauge location could have contributed to this effect.

As noted by Scazziga et al. [35], one of the challenges of interpreting strain responses measured in flexible pavements is the uncertainty associated with the "true" strain value generated by a given load.

2. CONCLUSIONS

Based on a review of literature and data analysis conducted in support of this research effort, the following conclusions can be made.

1. The layer characteristics and material properties of the instrumented pavement section are within expected ranges.
2. The test section subgrade appears to be saturated at some depth year around. This saturated condition triggers the stiff layer algorithm in EVERCALC 3.3. An appropriate modulus of elasticity to represent this layer in backcalculation is 40-50 ksi.

3. Layered elastic analysis is adequate for characterizing the layer properties of the test section.

4. The techniques and procedures used to install the instrumentation resulted in a successful installation.

5. The procedure used to determine the effective thicknesses of Sikadur® epoxy at each core, and the resulting thicknesses used in calculating theoretical strains, are reasonable.

6. The hardware, software, and data reduction and conversion techniques utilized in this study resulted in successful data collection and analysis.

7. The range of agreement between measured and calculated strains is, in general, ± 20 percent. Measured and calculated strains at all axial core surface longitudinal, bottom longitudinal, and bottom transverse strain gauges can be expected to agree within ± 20 percent.

8. Layered elastic analysis provides a realistic prediction of strain in a pavement structure due to application of a load.

9. The agreement between transverse and longitudinal strains and strain magnitude at any axial core gauge location is potentially affected by alignment of the load over the gauge.

3. RECOMMENDATIONS

The following recommendations are appropriate for further testing conducted at the test section.

1. Before any of the other, as yet unevaluated, gauges at the test section are used, FWD testing and data analysis should be conducted to evaluate the effective thickness of epoxy at each location.

2. Extreme care should be taken when centering the load over a gauge. This will become even more critical during truck testing. A system to guide,

evaluate, or measure transverse alignment of a moving truck will greatly enhance future data analysis.

3. Data should be filtered for low frequency noise during collection. This could consist of low pass filtering (20 hertz) or a digital filter card in the data collection hardware.

4. To reduce the volume of data, the sweep time could be reduced by use of an analog trigger during FWD testing or an optical control device for truck testing. This would ensure that data is collected only during the few seconds of gauge response.

5. To reduce the time involved in data reduction and conversion, a more automated software package could be utilized. An example is the in-house package used by PACCAR to analyze strain data. However, this should not be used to eliminate the manual review of strain-time plots to help evaluate the quality of the data.

6. Gauge 7ST should be considered unreliable and not used in any future testing.

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APPENDIX A

OCTOBER 1991 WSDOT FWD DEFLECTION DATA—PACCAR TEST SECTION

Table A-1. October 1991 WSDOT FWD Deflection Data - PACCAR Test Section

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
Unknown	4874	9.74	8.74	7.65	4.05	1.99	1.24
Unknown	4974	9.29	8.25	7.25	3.86	1.93	1.31
Unknown	4926	9.08	8.01	6.91	3.72	1.86	1.17
Unknown	4926	9.01	7.89	6.80	3.74	1.88	1.22
Unknown	10777	21.52	17.65	14.94	8.57	4.52	2.42
Unknown	10849	20.05	16.51	14.01	8.08	4.44	2.47
Unknown	10881	19.69	16.27	13.84	8.00	4.45	2.49
Unknown	10821	19.51	16.14	13.74	7.98	4.45	2.50
Unknown	10789	19.81	16.33	13.87	8.04	4.48	2.48
Unknown	10837	19.43	16.05	13.71	8.01	4.50	2.49
Unknown	10813	19.31	15.96	13.65	7.99	4.41	2.50
Unknown	10809	19.22	15.92	13.63	8.01	4.48	2.49
Unknown	10849	19.65	16.16	13.83	8.04	4.50	2.46
Unknown	10825	19.26	15.95	13.66	8.00	4.45	2.50
Unknown	10817	19.15	15.88	13.60	7.99	4.45	2.49
Unknown	10762	19.15	15.88	13.63	8.00	4.46	2.50
Unknown	10805	19.57	16.18	13.79	8.05	4.54	2.50
Unknown	10809	19.28	15.98	13.68	8.04	4.47	2.51
Unknown	10849	19.16	15.89	13.61	8.02	4.49	2.50
Unknown	10809	19.13	15.87	13.62	8.01	4.48	2.50
Unknown	10833	19.67	16.23	13.86	8.10	4.51	2.52
Unknown	10817	19.27	15.93	13.65	8.03	4.48	2.50
Unknown	10805	19.13	15.87	13.61	8.02	4.48	2.51
Unknown	10793	19.06	15.82	13.57	8.00	4.46	2.50
Core 5	14055	31.72	25.50	21.30	11.16	5.22	2.59
Core 5	14138	29.79	23.88	20.00	10.62	5.17	2.78
Core 5	10809	22.06	17.64	14.80	7.88	3.89	2.15
Core 5	10817	21.94	17.56	14.74	7.85	3.88	2.14
Core 5	9300	18.58	14.88	12.48	6.63	3.27	1.81
Core 5	9379	18.60	14.89	12.49	6.62	3.26	1.81
Core 5	5152	9.92	7.83	6.52	3.41	1.67	0.94
Core 5	5156	9.85	7.78	6.47	3.39	1.65	0.94
Core 5	14178	29.48	23.66	19.85	10.56	5.21	2.81
Core 5	14194	29.06	23.38	19.65	10.53	5.22	2.83
Core 5	10718	21.77	17.48	14.67	7.83	3.89	2.13

Table A-1. October 1991 WSDOT FWD Deflection Data - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
Core 5	10770	21.70	17.41	14.61	7.81	3.89	2.13
Core 5	9268	18.42	14.77	12.40	6.59	3.25	1.79
Core 5	9304	18.46	14.82	12.44	6.61	3.27	1.80
Core 5	5033	9.77	7.75	6.43	3.37	1.66	0.93
Core 5	5093	9.70	7.71	6.41	3.36	1.64	0.93
Core 4	13956	30.93	25.53	21.84	12.24	6.21	3.17
Core 4	14039	29.20	24.06	20.58	11.66	6.04	3.17
Core 4	10730	21.48	17.64	15.09	8.54	4.42	2.33
Core 4	10631	21.39	17.57	15.04	8.52	4.41	2.33
Core 4	9165	17.98	14.78	12.63	7.13	3.67	1.93
Core 4	9153	18.00	14.82	12.66	7.15	3.69	1.95
Core 4	5033	9.25	7.59	6.42	3.56	1.82	0.98
Core 4	5045	9.29	7.62	6.44	3.56	1.81	0.96
Core 4	14134	29.02	23.95	20.49	11.66	6.06	3.19
Core 4	14138	28.69	23.74	20.35	11.65	6.07	3.21
Core 4	10634	21.35	17.61	15.07	8.57	4.45	2.34
Core 4	10627	21.25	17.55	15.02	8.54	4.45	2.34
Core 4	9113	17.93	14.79	12.65	7.16	3.70	1.94
Core 4	9137	17.95	14.82	12.67	7.17	3.71	1.95
Core 4	5001	9.31	7.63	6.44	3.58	1.83	0.98
Core 4	5073	9.36	7.67	6.49	3.60	1.83	0.97
Core 3	13892	32.55	26.46	22.49	12.47	6.31	3.21
Core 3	14015	30.88	24.96	21.22	11.87	6.12	3.22
Core 3	10726	22.43	18.18	15.45	8.67	4.46	2.37
Core 3	10722	22.27	18.07	15.36	8.61	4.45	2.34
Core 3	9133	18.73	15.17	12.88	7.17	3.69	1.94
Core 3	9244	18.80	15.27	12.96	7.22	3.74	1.97
Core 3	5029	9.63	7.70	6.45	3.50	1.80	0.97
Core 3	5057	9.58	7.72	6.47	3.51	1.80	0.96
Core 3	13979	30.56	24.77	21.11	11.83	6.13	3.22
Core 3	14118	30.24	24.56	20.98	11.82	6.20	3.25
Core 3	10726	22.40	18.12	15.44	8.67	4.52	2.37
Core 3	10698	22.11	18.05	15.41	8.64	4.49	2.37
Core 3	9141	18.62	15.17	12.92	7.20	3.74	1.97

Table A-1. October 1991 WSDOT FWD Deflection Data - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils) 0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
Core 3	9188	18.69	15.25	12.99	7.25	3.75	1.98
Core 3	5081	9.69	7.78	6.54	3.56	1.82	0.97
Core 3	5081	9.74	7.82	6.56	3.56	1.83	0.98
Core 5	14142	30.61	24.10	20.17	10.53	5.10	2.72
Core 5	14249	29.89	23.59	19.79	10.46	5.20	2.81
Core 5	14202	29.89	23.57	19.82	10.48	5.18	2.82
Core 5	14257	29.79	23.57	19.80	10.47	5.19	2.83
Core 5	14226	30.26	23.87	20.01	10.49	5.17	2.83
Core 5	14198	29.76	23.56	19.77	10.46	5.18	2.83
Core 5	14230	29.73	23.56	19.78	10.48	5.20	2.83
Core 5	14226	29.66	23.49	19.74	10.46	5.19	2.82
Core 5	14174	30.08	23.71	19.84	10.54	5.20	2.83
Core 5	14226	29.56	23.41	19.62	10.52	5.28	2.86
Core 5	14230	29.43	23.35	19.60	10.51	5.24	2.87
Core 5	14210	29.39	23.33	19.60	10.51	5.24	2.86
Core 5	14142	29.42	13.13	19.46	10.50	5.25	2.84
Core 5	14214	29.37	23.09	19.40	10.51	5.30	2.91
Core 5	14226	29.29	23.03	19.41	10.55	5.30	2.90
Core 5	10809	22.13	17.35	14.59	7.86	3.97	2.17
Core 5	5256	10.30	7.93	6.59	3.50	1.71	0.94
MDD	13832	30.90	24.31	20.50	11.02	5.52	2.99
MDD	13848	30.07	23.72	19.88	10.72	5.50	3.07
MDD	13789	29.76	23.45	19.66	10.68	5.54	3.08
MDD	10623	22.23	16.42	14.54	7.88	4.13	2.31
MDD	5172	9.97	7.42	6.38	3.47	1.77	1.06
MDD	5160	9.93	7.30	6.30	3.43	1.76	1.03
MDD	13570	31.07	24.55	20.60	11.36	5.91	3.26
MDD	13602	30.33	23.71	19.90	11.02	5.84	3.27
MDD	10491	22.45	17.50	14.65	8.15	4.34	2.49
MDD	5176	10.11	7.59	6.38	3.58	1.85	1.07
MDD	5097	10.03	7.59	6.34	3.54	1.83	1.06
MDD	13372	31.74	24.54	20.66	11.63	6.31	3.38
MDD	10245	22.85	17.65	14.80	8.35	4.66	2.52
MDD	4942	10.04	7.75	6.44	3.56	1.95	1.05

Table A-1. October 1991 WSDOT FWD Deflection Data - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
MDD	13487	32.69	25.70	21.98	11.73	6.21	3.32
MDD	10253	23.47	18.46	15.78	8.44	4.50	2.52
MDD	4906	9.87	8.27	7.02	3.68	1.94	1.08
MDD	13229	30.56	26.14	20.93	11.54	6.17	3.30
MDD	13284	30.13	25.77	20.57	11.36	6.10	3.34
MDD	10146	22.78	19.67	15.63	8.58	4.60	2.53
MDD	5073	10.26	9.10	7.15	3.87	2.02	1.14
Core 4	13916	30.90	25.19	21.35	11.82	6.00	3.15
Core 4	14079	29.69	24.16	20.59	11.63	6.09	3.23
Core 4	10813	21.95	17.69	15.18	8.60	4.45	2.38
Core 4	5283	9.61	7.96	6.69	3.69	1.89	1.02
Core 3	14102	31.88	25.23	21.49	12.17	6.36	3.35
Core 3	10873	23.13	18.19	15.54	8.58	4.62	2.35
Core 3	5303	10.27	8.07	6.98	3.62	1.88	1.05
Core 2	14099	36.35	28.55	24.03	13.22	6.57	3.36
Core 2	10849	24.28	18.80	15.75	8.71	4.47	2.43
Core 2	5268	10.60	7.65	6.60	3.58	1.86	1.03
Core 1	13427	33.17	27.52	23.21	12.53	6.30	3.17
Core 1	13530	31.43	26.08	22.04	12.10	6.26	3.31
Core 1	10718	22.70	18.92	16.04	8.74	4.40	2.43
Core 1	5204	10.02	8.14	6.73	3.59	1.77	0.98
Shear Slot	13336	33.74	27.24	23.07	12.84	6.60	3.35
Shear Slot	13435	30.26	24.26	20.56	11.55	6.15	3.33
Shear Slot	10360	21.60	17.45	14.78	8.31	4.48	2.45
Shear Slot	10380	21.52	17.51	14.78	8.35	4.51	2.48
Shear Slot	13864	32.46	24.91	20.96	11.35	5.84	2.90
Shear Slot	10774	22.44	17.09	14.46	7.97	4.20	2.27

APPENDIX B

OCTOBER 1991 WSDOT FWD TESTING EVERCALC OUTPUT—PACCAR TEST SECTION

Table B-1. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 10 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	819826	2670	990487	2.7
Unknown	4926	870879	3048	1112312	1.6
Unknown	4926	896664	3110	979045	1.8
Unknown	4974	835472	3198	717407	3.0
Unknown	10777	940128	2547	1008548	2.7
Unknown	10821	1079142	2835	894390	2.9
Unknown	10849	1030547	2795	918630	2.9
Unknown	10881	1065450	2836	918269	2.9
Unknown	10789	1057679	2774	960841	3.1
Unknown	10809	1124623	2749	1065041	2.9
Unknown	10813	1097595	2823	975644	2.7
Unknown	10837	1093294	2801	976834	3.1
Unknown	10762	1118445	2769	943712	2.7
Unknown	10817	1123152	2766	985661	2.8
Unknown	10825	1132858	2726	1040808	2.8
Unknown	10849	1100169	2710	1034723	3.2
Unknown	10805	1108861	2702	1023489	3.2
Unknown	10809	1118505	2767	978267	2.7
Unknown	10809	1138655	2738	1041017	2.8
Unknown	10849	1138618	2751	1035121	2.9
Unknown	10793	1135884	2752	1001948	2.7
Unknown	10805	1140696	2731	1013156	2.7
Unknown	10817	1120409	2756	982005	2.8
Unknown	10833	1088466	2754	917733	2.9
Core 5	5152	763502	3383	2000001	3.2
Core 5	5156	762703	3432	2000001	3.1
Core 5	9300	775719	3056	1888947	2.7
Core 5	9379	784199	3068	1967228	2.7
Core 5	10809	774794	2944	1853103	2.7
Core 5	10817	784972	2949	1920918	2.7
Core 5	14055	667897	2654	2000001	3.1
Core 5	14138	756109	2793	2000001	2.6
Core 5	5033	774702	3280	1962053	3.2
Core 5	5093	777885	3368	2000001	2.9

Table B-1. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 10 ksi - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	796660	2995	1987962	2.6
Core 5	9304	800176	2997	2000001	2.7
Core 5	10718	791037	2903	1856912	2.7
Core 5	10770	805906	2913	1944261	2.8
Core 5	14178	783202	2779	2000001	2.7
Core 5	14194	797407	2819	1935356	2.6
Core 4	5033	941647	2889	1849064	2.6
Core 4	5045	932959	2895	1922954	2.6
Core 4	9153	946972	2506	1745156	2.3
Core 4	9165	940993	2525	1750120	2.3
Core 4	10631	927908	2464	1542324	2.3
Core 4	10730	921152	2508	1504058	2.4
Core 4	13956	845526	2177	1517894	2.0
Core 4	14039	910214	2350	1477961	2.2
Core 4	5001	924726	2881	1720180	2.7
Core 4	5073	925591	2893	1859895	2.6
Core 4	9113	952195	2473	1801063	2.3
Core 4	9137	955159	2482	1783951	2.3
Core 4	10627	950584	2416	1653695	2.3
Core 4	10634	945151	2413	1637797	2.3
Core 4	14134	921784	2381	1456938	2.2
Core 4	14138	941628	2373	1496565	2.1
Core 3	5029	866017	3014	1556953	3.4
Core 3	5057	879856	2979	1734517	3.3
Core 3	9133	874294	2557	1487116	2.8
Core 3	9244	880245	2593	1425721	2.8
Core 3	10722	885010	2467	1474212	2.7
Core 3	10726	866600	2507	1298149	2.6
Core 3	13892	786793	2151	1299240	2.4
Core 3	14015	833955	2362	1203493	2.6
Core 3	5081	866620	3010	1604534	3.3
Core 3	5081	873159	2965	1623048	3.3
Core 3	9141	896527	2528	1493363	2.6
Core 3	9188	895757	2527	1495944	2.5

Table B-1. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 10 ksi - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	904559	2432	1509500	2.5
Core 3	10726	891102	2438	1457278	2.8
Core 3	13979	853472	2324	1270530	2.6
Core 3	14118	889304	2333	1363157	2.7
Core 5	14142	709642	2850	1749349	3.1
Core 5	14202	762087	2859	1763425	3.0
Core 5	14249	765871	2864	1817964	3.1
Core 5	14257	763054	2883	1759232	3.0
Core 5	14198	761504	2879	1736110	2.9
Core 5	14226	737910	2894	1653136	3.0
Core 5	14226	766142	2884	1742867	3.0
Core 5	14230	768020	2866	1764666	3.0
Core 5	14174	757644	2842	1653174	3.1
Core 5	14210	787741	2861	1665113	3.0
Core 5	14226	787666	2846	1677757	3.2
Core 5	14230	787479	2868	1661138	3.0
Core 5	14142	1347703	3297	2000001	21.1
Core 5	14214	803380	2884	1444085	3.3
Core 5	14226	814955	2853	1557694	3.3
Core 5	10809	806017	2919	1522795	3.4
Core 5	5256	753894	3396	2000001	4.3
MDD	13832	746165	2651	1271772	3.0
MDD	13848	767439	2792	956631	3.1
MDD	13789	784433	2801	855133	3.3
MDD	10623	838746	2939	88564	4.4
MDD	5172	838412	3476	1135268	4.3
MDD	5160	854813	3449	1201231	4.8
MDD	13570	767646	2557	691307	3.1
MDD	13602	784116	2724	542993	3.5
MDD	10491	814817	2898	532079	3.6
MDD	5176	875049	3276	1045066	4.8
MDD	5097	855911	3263	1004147	4.6
MDD	13372	790662	2415	640619	4.2
MDD	10245	851800	2591	684571	4.6

Table B-1. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 10 ksi - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	877825	2938	1077090	5.0
MDD	13487	725196	2389	717793	3.1
MDD	10253	757313	2635	535677	2.9
MDD	4906	816927	2826	921125	2.0
MDD	13229	753631	2384	686908	3.1
MDD	13284	764732	2482	577569	3.1
MDD	10146	761632	2519	574329	3.1
MDD	5073	785479	2866	805925	3.1
Core 4	13916	813805	2341	1354881	2.3
Core 4	14079	891306	2405	1224481	2.6
Core 4	10813	914995	2533	1295982	2.6
Core 4	5283	942892	2917	2000001	2.6
Core 3	14102	848205	2291	1100403	3.3
Core 3	10873	875554	2479	1724654	4.1
Core 3	5303	829717	3134	1351295	3.1
Core 2	14099	689536	2145	1122336	3.1
Core 2	10849	789444	2620	988691	3.8
Core 2	5268	859114	3182	1279780	5.6
Core 1	13427	718829	2068	1373615	2.0
Core 1	13530	779026	2235	949191	1.9
Core 1	10718	809378	2551	1286476	1.4
Shear Slot	5204	798714	3172	2000001	2.8
Shear Slot	13336	745149	2007	1120420	2.6
Shear Slot	13435	831134	2389	748403	2.9
Shear Slot	10360	896664	2568	857597	3.0
Shear Slot	10380	898312	2593	783524	2.9
Shear Slot	13864	753262	2429	1624840	4.5
Shear Slot	10774	849487	2842	1076586	4.5

Table B-2. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 25 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	639514	6732	15361	4.5
Unknown	4926	760587	6763	19692	3.5
Unknown	4926	749635	8184	17060	3.6
Unknown	4974	674230	8187	14350	5.2
Unknown	10777	921609	3594	35866	1.1
Unknown	10821	1004330	4959	26940	1.2
Unknown	10849	968964	4688	28382	1.2
Unknown	10881	997343	4848	27974	1.2
Unknown	10789	1001029	4587	28705	1.4
Unknown	10809	1103409	4076	35052	1.2
Unknown	10813	1033278	4774	28538	0.9
Unknown	10837	1077292	4207	33263	1.4
Unknown	10762	1081205	4353	31103	1.0
Unknown	10817	1092782	4251	33161	1.0
Unknown	10825	1062601	4516	30305	1.0
Unknown	10849	1079235	3912	37255	1.5
Unknown	10805	1064827	4228	31706	1.5
Unknown	10809	1067125	4462	30242	1.0
Unknown	10809	1105427	4170	33650	1.1
Unknown	10849	1119629	4052	35622	1.1
Unknown	10793	1105003	4226	33041	1.0
Unknown	10805	1098939	4281	32117	1.0
Unknown	10817	1091988	4215	32936	1.1
Unknown	10833	1027685	4623	28166	1.2
Core 5	5152	758387	4227	73528	1.1
Core 5	5156	755745	4330	72165	1.0
Core 5	9300	755672	4061	53260	0.8
Core 5	9379	758679	4074	56189	0.7
Core 5	10809	737921	4121	44341	0.9
Core 5	10817	744885	4101	47113	0.8
Core 5	14055	707316	2779	122955	0.9
Core 5	14138	729656	3679	52934	0.8
Core 5	5033	751473	4273	64336	1.1
Core 5	5093	762729	4291	70926	0.9

Table B-2. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 25 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	768355	3959	57372	0.7
Core 5	9304	768355	3959	57372	0.7
Core 5	10718	754691	4017	46986	0.8
Core 5	10770	764440	4003	49421	0.8
Core 5	14178	741538	3806	49300	0.8
Core 5	14194	761968	3829	49794	0.8
Core 4	5033	962568	3429	83395	0.7
Core 4	5045	970662	3248	109490	0.7
Core 4	9153	960005	2970	76883	0.7
Core 4	9165	960005	2970	76883	0.6
Core 4	10631	935908	3048	58418	0.7
Core 4	10730	935908	3048	58418	0.7
Core 4	13956	835226	2775	46481	0.4
Core 4	14039	895753	3052	45289	0.6
Core 4	5001	956885	3372	81369	0.9
Core 4	5073	978523	3199	112134	0.7
Core 4	9113	969656	2900	78231	0.6
Core 4	9137	969656	2900	78231	0.6
Core 4	10627	950512	2947	60447	0.8
Core 4	10634	950512	2947	60447	0.6
Core 4	14134	919198	3051	47381	0.6
Core 4	14138	919198	3051	47381	0.9
Core 3	5029	860896	3860	61109	1.5
Core 3	5057	888203	3629	76405	1.3
Core 3	9133	866858	3314	49499	1.1
Core 3	9244	876218	3354	48589	1.1
Core 3	10722	864431	3319	43470	1.1
Core 3	10726	838918	3556	36040	1.0
Core 3	13892	745427	3159	29379	0.9
Core 3	14015	781043	3730	26879	1.1
Core 3	5081	889481	3579	76259	1.3
Core 3	5081	869346	3737	64815	1.4
Core 3	9141	879286	3338	46561	1.0
Core 3	9188	879286	3338	46561	0.9

Table B-2. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 25 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	869741	3309	41594	0.9
Core 3	10726	869741	3309	41594	1.2
Core 3	13979	800150	3626	28108	1.1
Core 3	14118	844928	3444	31852	1.2
Core 5	14142	687777	3783	50242	1.2
Core 5	14202	709233	4160	40943	1.2
Core 5	14249	719205	4057	43989	1.3
Core 5	14257	714422	4180	41264	1.1
Core 5	14198	708565	4234	39548	1.1
Core 5	14226	679244	4379	36598	1.1
Core 5	14226	724401	4082	43336	1.2
Core 5	14230	717960	4150	41367	1.1
Core 5	14174	700164	4232	38019	1.3
Core 5	14210	739847	4158	40331	1.2
Core 5	14226	740149	4130	40468	1.4
Core 5	14230	734231	4249	38766	1.2
Core 5	14142	1580546	3057	271925	20.8
Core 5	14214	739711	4485	34277	1.5
Core 5	14226	758292	4251	37874	1.5
Core 5	10809	751762	4338	38869	1.6
Core 5	5256	784192	3899	97760	2.0
MDD	13832	659339	4765	23776	1.4
MDD	13848	639436	5986	20159	1.3
MDD	13789	655055	5997	20087	1.5
MDD	10623	725923	5766	23613	3.2
MDD	5172	712604	6787	28049	2.7
MDD	5160	753668	6052	32634	3.1
MDD	13570	614164	6403	15875	1.5
MDD	13602	614880	7167	16053	1.9
MDD	10491	622618	7910	16761	1.9
MDD	5176	752786	6198	28044	3.0
MDD	5097	728391	6404	26620	2.8
MDD	13372	606404	7062	13490	2.7
MDD	10245	638134	7793	14560	3.0

Table B-2. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 25 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	762770	5522	25791	3.2
MDD	13487	568269	6449	13866	1.7
MDD	10253	569994	7536	14681	1.4
MDD	4906	722031	5357	23455	1.1
MDD	13229	611476	6162	14156	1.9
MDD	13284	598580	6896	14007	1.9
MDD	10146	598652	6876	14349	2.0
MDD	5073	676875	5945	20559	2.5
Core 4	13916	757122	3644	27707	0.8
Core 4	14079	845324	3658	30120	1.1
Core 4	10813	897047	3450	41211	1.1
Core 4	5283	957745	3475	90438	0.7
Core 3	14102	761102	4121	21669	1.9
Core 3	10873	862150	3244	47668	2.6
Core 3	5303	764186	4900	37483	1.5
Core 2	14099	600195	4273	16502	1.8
Core 2	10849	664206	5381	20429	2.2
Core 2	5268	774542	5059	37513	3.9
Core 1	13[illegible]	656147	3489	20601	0.7
Core 1	13530	680616	4541	17259	0.5
Core 1	10718	727825	4547	22605	1.0
Shear Slot	5204	791485	3945	69101	0.9
Shear Slot	13336	655550	3975	16041	1.3
Shear Slot	13435	692714	5646	16407	1.5
Shear Slot	10360	773562	5371	19794	1.4
Shear Slot	10380	776526	5510	19241	1.3
Shear Slot	13864	731314	3214	42912	3.0
Shear Slot	10774	760546	4904	28381	2.9

Table B-3. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 40 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	531118	17462	7771	5.9
Unknown	4926	562679	19398	8871	5.1
Unknown	4926	542707	21987	8502	5.3
Unknown	4974	504441	22835	7964	6.9
Unknown	10777	666632	12206	10601	1.0
Unknown	10821	676106	17292	10629	0.8
Unknown	10849	671594	16183	10595	0.8
Unknown	10881	676106	17292	10629	0.6
Unknown	10789	669629	17177	10332	0.8
Unknown	10809	714894	17132	10455	1.0
Unknown	10813	714894	17132	10455	1.0
Unknown	10837	714894	17132	10455	0.9
Unknown	10762	729704	16761	10707	0.9
Unknown	10817	729704	16761	10707	0.9
Unknown	10825	729704	16761	10707	0.8
Unknown	10849	736409	15362	10879	1.1
Unknown	10805	711451	16753	10423	1.0
Unknown	10809	727801	16946	10516	0.8
Unknown	10809	757804	16506	10666	0.9
Unknown	10849	757804	16506	10666	0.9
Unknown	10793	739082	16604	10648	0.9
Unknown	10805	739082	16604	10648	0.9
Unknown	10817	739082	16604	10648	0.9
Unknown	10833	697128	17006	10447	0.8
Core 5	5152	496417	15874	12042	1.5
Core 5	5156	495249	16103	12186	1.8
Core 5	9300	502768	15588	10584	1.5
Core 5	9379	505469	15572	10781	1.6
Core 5	10809	484895	15855	10114	1.6
Core 5	10817	493293	15710	10222	1.5
Core 5	14055	522582	9494	10620	0.9
Core 5	14138	492936	14021	10037	1.4
Core 5	5033	493548	15773	11881	1.4
Core 5	5093	508292	15602	12327	1.7

Table B-3. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 40 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	519022	14925	10898	1.4
Core 5	9304	519812	15009	10872	1.4
Core 5	10718	504124	15249	10277	1.3
Core 5	10770	510519	13512	10395	1.3
Core 5	14178	501113	14343	10150	1.2
Core 5	14194	516119	14615	10615	1.3
Core 4	5033	709022	11869	12503	0.8
Core 4	5045	731217	10688	13185	0.6
Core 4	9153	711898	10896	10926	0.9
Core 4	9165	711898	10896	10926	0.8
Core 4	10631	678106	11634	10140	0.9
Core 4	10730	684380	11475	10285	0.8
Core 4	13956	626943	9809	9222	0.8
Core 4	14039	654794	11420	9542	0.8
Core 4	5001	701900	11784	12290	0.8
Core 4	5073	735895	10632	13096	0.6
Core 4	9113	721635	10689	10791	0.7
Core 4	9137	751635	10689	10791	0.7
Core 4	10627	696962	11258	10131	0.8
Core 4	10634	696962	11258	10131	0.8
Core 4	14134	669104	11631	9622	0.8
Core 4	14138	688903	11648	9642	0.8
Core 3	5029	593354	13895	12004	1.0
Core 3	5057	627858	12725	12579	0.6
Core 3	9133	614103	12303	10287	0.9
Core 3	9244	614103	12303	10287	1.0
Core 3	10722	608699	12536	9836	0.9
Core 3	10726	588637	13057	9369	1.0
Core 3	13892	539943	10871	8543	0.9
Core 3	14015	544268	13133	8873	1.0
Core 3	5081	629648	12523	12503	0.7
Core 3	5081	629648	12523	12503	0.9
Core 3	9141	624479	12490	10122	0.8
Core 3	9188	624479	12490	10122	0.8

Table B-3. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 40 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	605979	12754	9644	0.9
Core 3	10726	605979	12754	9644	1.0
Core 3	13979	559394	13033	8876	1.0
Core 3	14118	586713	13082	8988	1.0
Core 5	14142	461075	13615	10408	1.3
Core 5	14202	465352	15285	10135	1.4
Core 5	14249	470483	15164	10219	1.2
Core 5	14257	469468	15380	10180	1.3
Core 5	14198	465077	15461	10119	1.4
Core 5	14226	477494	15180	10212	1.3
Core 5	14226	444416	15494	10079	1.4
Core 5	14230	473073	15296	10155	1.3
Core 5	14174	460970	15071	10194	1.4
Core 5	14210	489696	15302	10221	1.3
Core 5	14226	485119	15380	10173	1.1
Core 5	14230	484147	15532	10173	1.3
Core 5	14142	1760417	2848	78268	20.7
Core 5	14214	481588	15990	10291	1.3
Core 5	14226	496723	15615	10306	1.4
Core 5	10809	489515	15717	10625	1.3
Core 5	5256	497797	15447	12152	1.6
MDD	13832	431335	15732	8983	1.4
MDD	13848	414674	17456	9373	1.3
MDD	13789	425841	17313	9554	1.1
MDD	10623	445644	18414	10342	2.9
MDD	5172	416810	22143	11336	2.8
MDD	5160	435983	21107	11803	2.8
MDD	13570	403582	16985	8583	1.2
MDD	13602	396532	18169	9135	1.2
MDD	10491	395193	19733	9647	1.3
MDD	5176	439490	20768	11366	2.4
MDD	5097	428731	20740	11226	0.2
MDD	13372	368107	18853	7780	1.7
MDD	10245	370136	21313	8297	1.8

Table B-3. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 40 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	445618	19449	10325	1.8
MDD	13487	374264	16603	7738	1.2
MDD	10253	379205	17840	8687	1.2
MDD	4906	517063	15362	10136	1.6
MDD	13229	425260	15797	7818	1.3
MDD	13284	416622	16590	8150	1.4
MDD	10146	420905	16437	8307	1.7
MDD	5073	485966	16009	9775	2.7
Core 4	13916	536407	12701	8809	0.9
Core 4	14079	588784	13284	9262	0.9
Core 4	10813	636948	12624	10223	1.3
Core 4	5283	700348	12317	12350	0.9
Core 3	14102	506902	14336	8502	1.6
Core 3	10873	548300	14691	9126	1.8
Core 3	5303	511560	16283	11639	1.5
Core 2	14099	401242	13437	7258	1.5
Core 2	10849	421952	16610	9201	1.6
Core 2	5268	446708	18509	11974	3.1
Core 1	13427	471316	11731	7367	0.8
Core 1	13530	486693	13349	7922	0.7
Core 1	10718	517997	14804	8773	1.8
Shear Slot	5204	537836	14906	11481	1.3
Shear Slot	13336	453668	12774	7039	1.0
Shear Slot	13435	462972	16201	8310	1.0
Shear Slot	10360	513696	16707	9169	0.8
Shear Slot	10380	513696	16707	9169	0.8
Shear Slot	13864	457569	13533	8861	2.0
Shear Slot	10774	472221	16855	10587	2.0

Table B-4. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	478441	21591	6693	6.4
Unknown	4926	499506	24426	7530	5.6
Unknown	4926	481166	27806	7262	5.9
Unknown	4974	454423	27402	6866	7.5
Unknown	10777	571646	16986	8978	1.0
Unknown	10821	567979	23264	9095	0.8
Unknown	10849	565247	21974	9076	0.7
Unknown	10881	567979	23264	9095	0.6
Unknown	10789	561038	23145	8835	0.6
Unknown	10809	585330	23984	8929	0.9
Unknown	10813	585330	23984	8929	0.9
Unknown	10837	597555	23386	8907	0.8
Unknown	10762	612503	22910	9138	0.9
Unknown	10817	612503	22910	9138	0.8
Unknown	10825	612503	22910	9138	0.8
Unknown	10849	585330	23984	8929	0.9
Unknown	10805	594802	22885	8900	0.8
Unknown	10809	610936	23130	8972	0.8
Unknown	10809	634837	22842	9063	0.8
Unknown	10849	634837	22842	9063	0.8
Unknown	10793	619721	22806	9075	0.9
Unknown	10805	619721	22806	9075	0.9
Unknown	10817	619721	22806	9075	0.9
Unknown	10833	584153	23016	8948	0.8
Core 5	5152	409232	22138	9729	2.5
Core 5	5156	408865	22412	9839	2.8
Core 5	9300	421170	21292	8696	2.4
Core 5	9379	42323[illegible]	21342	8835	2.4
Core 5	10809	415627	19199	8278	2.4
Core 5	10817	414117	21262	8445	2.3
Core 5	14055	447372	13912	8456	1.6
Core 5	14138	415627	19199	8278	2.2
Core 5	5033	408712	21829	9660	2.3
Core 5	5093	421575	21786	9959	2.6

Table B-4. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	435365	20597	8931	2.2
Core 5	9304	436184	20688	8914	2.2
Core 5	10718	424132	20707	8504	2.1
Core 5	10770	428278	20884	8584	2.0
Core 5	14178	422584	19578	8395	2.0
Core 5	14194	434860	19994	8401	2.0
Core 4	5033	602346	17496	10166	1.1
Core 4	5045	622841	16247	10443	0.9
Core 4	9153	600374	16421	8807	1.1
Core 4	9165	610346	15991	8946	1.1
Core 4	10631	581018	16646	8421	1.1
Core 4	10730	586673	16516	8531	1.1
Core 4	13956	548132	13771	7742	0.2
Core 4	14039	562600	16238	8003	1.1
Core 4	5001	595718	17291	10021	1.0
Core 4	5073	627012	16174	10382	1.0
Core 4	9113	619699	15756	8826	1.0
Core 4	9137	616391	15972	8802	1.0
Core 4	10627	601854	16335	8400	1.0
Core 4	10634	598601	16231	8396	1.1
Core 4	14134	575949	16417	8063	1.1
Core 4	14138	592896	16550	8057	1.1
Core 3	5029	493076	19554	10003	0.9
Core 3	5057	527378	18401	10223	0.8
Core 3	9133	522273	17288	8581	1.1
Core 3	9244	525907	17622	8573	1.0
Core 3	10722	518936	17408	8260	1.1
Core 3	10726	501341	17911	8137	1.3
Core 3	13892	469291	14645	7319	1.1
Core 3	14015	465747	17567	7587	1.2
Core 3	5081	507305	18915	9992	0.9
Core 3	5081	527762	18198	10146	0.9
Core 3	9141	532269	17496	8461	1.0
Core 3	9188	536976	17332	8483	1.0

Table B-4. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	529304	17465	8149	1.1
Core 3	10726	514609	17688	8121	1.1
Core 3	13979	479261	17475	7595	1.2
Core 3	14118	501767	17738	7653	1.1
Core 5	14142	386295	18620	8599	2.0
Core 5	14202	389306	20549	8435	2.1
Core 5	14249	392973	20479	8489	1.9
Core 5	14257	393045	20685	8467	2.1
Core 5	14198	389838	20717	8430	2.1
Core 5	14226	399970	20493	8484	2.0
Core 5	14226	373147	20605	8416	2.2
Core 5	14230	396416	20585	8448	2.0
Core 5	14174	386033	20202	8516	2.0
Core 5	14210	410230	20635	8520	1.9
Core 5	14226	405137	20731	8487	1.7
Core 5	14230	405584	20863	8512	2.0
Core 5	14142	1000000	22675	9802	21.7
Core 5	14214	401242	21348	8649	1.8
Core 5	14226	413673	21041	8630	1.9
Core 5	10809	406584	21193	8886	1.7
Core 5	5256	401793	21978	9762	2.1
MDD	13832	363914	20373	7664	2.0
MDD	13848	350594	22103	8080	1.8
MDD	13789	359108	21969	8263	1.5
MDD	10623	362617	23897	8900	2.9
MDD	5172	336678	28574	9577	3.2
MDD	5160	346502	27788	9936	3.0
MDD	13570	343098	21117	7529	1.5
MDD	13602	334714	22451	8051	1.4
MDD	10491	332026	24304	8492	1.5
MDD	5176	350888	27097	9674	2.4
MDD	5097	345326	26842	9575	2.3
MDD	13372	303076	23100	6884	1.4
MDD	10245	303876	26107	7310	1.3

Table B-4. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	359489	25266	8847	1.2
MDD	13487	320684	20378	6813	1.4
MDD	10253	325826	21734	7680	1.6
MDD	4906	450380	19852	8681	2.1
MDD	13229	371579	19444	6879	1.4
MDD	13284	364606	20232	7202	1.6
MDD	10146	369427	20069	7332	2.0
MDD	5073	425752	20300	8423	3.1
Core 4	13916	461776	17014	7500	1.3
Core 4	14079	505343	17994	7902	1.1
Core 4	10813	541387	17663	8589	1.5
Core 4	5283	597252	18020	10104	1.1
Core 3	14102	427745	18816	7355	1.6
Core 3	10873	452686	20131	7691	1.5
Core 3	5303	428992	21888	9725	2.0
Core 2	14099	342809	17091	6318	1.7
Core 2	10849	350920	21297	7956	1.7
Core 2	5268	347049	25047	10090	2.8
Core 1	13427	416739	14954	6420	1.2
Core 1	13530	425333	17141	6916	1.2
Core 1	10718	450014	19277	7478	2.4
Shear Slot	5204	449954	20871	9314	2.2
Shear Slot	13336	392475	16329	6148	1.1
Shear Slot	13435	394348	20424	7289	1.1
Shear Slot	10360	435617	21446	7969	0.9
Shear Slot	10380	435617	21446	7969	1.0
Shear Slot	13864	376193	18340	7488	1.6
Shear Slot	10774	383339	22376	9043	1.8

Table B-5. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 75 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	418655	26806	5598	7.0
Unknown	4926	427541	30842	6192	6.4
Unknown	4926	411447	33540	6000	6.6
Unknown	4974	396659	33207	5723	8.2
Unknown	10777	455807	23715	7485	1.3
Unknown	10821	445862	31716	7528	0.9
Unknown	10849	438486	29885	7592	1.0
Unknown	10881	444919	31190	7596	0.9
Unknown	10789	437790	31031	7379	0.8
Unknown	10809	481785	31530	7416	0.9
Unknown	10813	457210	32175	7439	1.3
Unknown	10837	463830	31674	7414	0.8
Unknown	10762	486561	30922	7565	1.0
Unknown	10817	490307	30906	7646	1.0
Unknown	10825	477769	31135	7622	1.0
Unknown	10849	477036	31135	7622	0.8
Unknown	10805	461646	31033	7431	0.6
Unknown	10809	492738	31315	7535	1.0
Unknown	10809	477005	31348	7480	1.1
Unknown	10849	492738	31315	7535	0.9
Unknown	10793	494956	31131	7574	1.0
Unknown	10805	489807	31273	7543	1.0
Unknown	10817	481949	31101	7565	1.0
Unknown	10833	454863	31023	7486	1.0
Core 5	5152	320544	30319	7688	3.9
Core 5	5156	321016	30660	7764	4.2
Core 5	9300	335538	28666	6981	3.6
Core 5	9379	336686	28829	7075	3.6
Core 5	10809	325536	28431	6766	3.5
Core 5	10817	330604	28429	6811	3.5
Core 5	14055	358730	20036	6750	2.7
Core 5	14138	332525	25945	6691	3.3
Core 5	5033	321127	29778	7679	3.7
Core 5	5093	331232	29965	7874	4.0

Table B-5. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 75 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	346104	28016	7166	3.4
Core 5	9304	347044	28106	7154	3.3
Core 5	10718	338937	27784	6877	3.2
Core 5	10770	341084	28105	6930	3.1
Core 5	14178	338331	26395	6800	3.1
Core 5	14194	347167	26997	6798	3.0
Core 4	5033	475676	25555	8135	1.9
Core 4	5045	490869	24298	8297	1.7
Core 4	9153	480000	23560	7181	1.6
Core 4	9165	487420	23195	7268	1.6
Core 4	10631	465309	23519	6918	1.6
Core 4	10730	469391	23462	6993	1.6
Core 4	13956	450058	19387	6422	1.6
Core 4	14039	454194	22646	6625	1.6
Core 4	5001	470236	25211	8038	1.8
Core 4	5073	493930	24209	8254	1.7
Core 4	9113	496231	22886	7178	1.5
Core 4	9137	493583	23106	7166	1.5
Core 4	10627	482611	23257	6892	1.5
Core 4	10634	480007	23117	6890	1.5
Core 4	14134	463915	22986	6664	1.5
Core 4	14138	477160	23255	6652	1.6
Core 3	5029	383787	27388	8087	1.8
Core 3	5057	410968	26291	8214	1.6
Core 3	9133	415009	24089	7053	1.6
Core 3	9244	417774	24500	7048	1.5
Core 3	10722	413566	24034	6825	1.6
Core 3	10726	400584	24410	6748	1.8
Core 3	13892	383908	19858	6148	1.6
Core 3	14015	374360	23487	6360	1.7
Core 3	5081	411258	26073	8158	1.7
Core 3	5081	396121	26662	8072	1.7
Core 3	9141	424828	24270	6972	1.5
Core 3	9188	429158	24104	6981	1.6

Table B-5. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 75 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	424133	24036	6745	1.6
Core 3	10726	408565	24319	6728	1.5
Core 3	13979	385794	23444	6362	1.6
Core 3	14118	401650	23983	6393	1.4
Core 5	14142	306800	25206	6968	3.2
Core 5	14202	309457	27377	6855	3.2
Core 5	14249	311681	27372	6890	3.0
Core 5	14257	312967	27552	6876	3.2
Core 5	14198	310525	27539	6854	3.2
Core 5	14226	318240	27388	6886	3.1
Core 5	14226	298609	27234	6854	3.4
Core 5	14230	315340	27457	6862	3.1
Core 5	14174	306944	26889	6948	3.1
Core 5	14210	325578	27579	6939	3.0
Core 5	14226	320495	27680	6917	2.7
Core 5	14230	322219	27794	6936	3.0
Core 5	14142	355365	50000	7329	21.6
Core 5	14214	316238	28328	7092	2.7
Core 5	14226	324733	28143	7057	2.7
Core 5	10809	318690	28365	7257	2.6
Core 5	5256	305634	30497	7695	3.3
MDD	13832	292341	26357	6372	2.8
MDD	13848	282388	28143	6773	2.7
MDD	13789	287731	28045	6954	2.3
MDD	10623	275732	31122	7454	3.2
MDD	5172	259391	36862	7830	4.2
MDD	5160	260463	36445	8110	3.7
MDD	13570	277791	26480	6433	2.1
MDD	13602	268534	28040	6908	1.9
MDD	10491	265587	30259	7270	2.1
MDD	5176	264459	35284	7993	2.9
MDD	5097	263595	34730	7925	2.9
MDD	13372	241991	28520	5932	1.3
MDD	10245	240108	31952	6255	1.0

Table B-5. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 75 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	274451	32697	7372	0.9
MDD	13487	262820	25240	5842	2.1
MDD	10253	267925	26811	6610	2.3
MDD	4906	373554	25866	7246	2.9
MDD	13229	310887	24185	5898	1.9
MDD	13284	306066	24976	6198	2.2
MDD	10146	311002	24824	6303	2.5
MDD	5073	359583	25876	7068	3.7
Core 4	13916	375529	22741	6264	2.0
Core 4	14079	404709	24317	6605	1.5
Core 4	10813	428982	24544	7109	1.9
Core 4	5283	473107	26177	8058	1.9
Core 3	14102	338209	24717	6226	1.8
Core 3	10873	348919	27166	6352	1.4
Core 3	5303	340051	29346	7925	3.1
Core 2	14099	277909	21818	5375	2.2
Core 2	10849	275924	27381	6704	2.2
Core 2	5268	251762	33559	8288	2.9
Core 1	13427	348253	19552	5420	1.9
Core 1	13530	353670	22059	5883	1.8
Core 1	10718	372788	25108	6219	3.2
Shear Slot	5204	357078	28674	7409	3.4
Shear Slot	13336	322176	20955	5255	1.5
Shear Slot	13435	317786	25931	6236	1.5
Shear Slot	10360	349564	27732	6774	1.3
Shear Slot	10380	355825	27704	6801	1.3
Shear Slot	13864	289740	24563	6208	1.6
Shear Slot	10774	291097	29604	7537	1.8

Table B-6. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 100 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	392027	29284	5151	7.3
Unknown	4926	397186	33838	5655	6.8
Unknown	4926	382111	36557	5489	7.0
Unknown	4974	371903	35929	5254	8.5
Unknown	10777	405652	27030	6894	1.5
Unknown	10821	394909	35545	9629	1.2
Unknown	10849	388653	33562	6986	1.3
Unknown	10881	394279	35015	6986	1.2
Unknown	10789	387260	34821	6789	1.0
Unknown	10809	424567	35532	6811	1.1
Unknown	10813	404348	36102	6835	1.6
Unknown	10837	408683	35465	6811	0.9
Unknown	10762	429331	34888	6957	1.2
Unknown	10817	432336	34914	7027	1.2
Unknown	10825	421600	35101	7009	1.2
Unknown	10849	419296	33662	7056	0.9
Unknown	10805	406373	34952	6837	0.8
Unknown	10809	433548	35264	6898	1.1
Unknown	10809	420798	35314	6877	1.3
Unknown	10849	433487	35391	6921	1.1
Unknown	10793	436002	35176	6961	1.2
Unknown	10805	431318	35307	6934	1.2
Unknown	10817	424941	35083	6956	1.1
Unknown	10833	402455	34836	6893	1.1
Core 5	5152	287730	34166	6909	4.6
Core 5	5156	288466	34544	6972	4.9
Core 5	9300	302688	32118	6318	4.1
Core 5	9379	303441	32343	6396	4.2
Core 5	10809	293818	31758	6139	4.1
Core 5	10817	298166	31794	6175	4.0
Core 5	14055	322794	22958	6123	3.2
Core 5	14138	299727	29131	6076	3.8
Core 5	5033	288903	33499	6918	4.3
Core 5	5093	297220	33839	7078	4.7

Table B-6. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 100 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	311334	31514	6485	4.0
Core 5	9304	312291	31603	6475	3.9
Core 5	10718	305097	31139	6242	3.7
Core 5	10770	307244	31493	6286	3.7
Core 5	14178	304646	29630	6179	3.6
Core 5	14194	312760	30287	6175	3.6
Core 4	5033	422741	29470	7372	2.3
Core 4	5045	435226	28262	7503	2.1
Core 4	9153	428619	27015	6559	1.9
Core 4	9165	434717	26694	6631	1.9
Core 4	10631	416094	26829	6336	1.9
Core 4	10730	419167	26823	6400	1.9
Core 4	13956	407209	22119	5913	1.9
Core 4	14039	407777	25733	6087	1.8
Core 4	5001	417500	29065	7292	2.2
Core 4	5073	437599	28177	7467	2.1
Core 4	9113	442603	26367	6553	1.8
Core 4	9137	440292	26587	6544	1.8
Core 4	10627	431457	26599	6311	1.7
Core 4	10634	429302	26437	6310	1.8
Core 4	14134	415740	26157	6119	1.8
Core 4	14138	427577	26477	6107	1.8
Core 3	5029	340134	31166	7344	2.3
Core 3	5057	363809	30138	7446	2.1
Core 3	9133	370186	27366	6458	1.9
Core 3	9244	372700	27806	6453	1.8
Core 3	10722	369203	27228	6262	1.9
Core 3	10726	358144	27543	6198	2.1
Core 3	13892	347178	22381	5683	1.9
Core 3	14015	336364	26318	5867	2.0
Core 3	5081	363892	29893	7400	2.1
Core 3	5081	651410	30408	7331	2.2
Core 3	9141	379582	27537	6387	1.8
Core 3	9188	383681	27370	6395	1.9

Table B-6. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 100 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	379520	27204	6192	1.9
Core 3	10726	364428	27496	6179	1.7
Core 3	13979	346539	26306	5868	1.9
Core 3	14118	259444	26980	5891	1.7
Core 5	14142	276447	28307	6334	3.8
Core 5	14202	278700	30597	6235	3.8
Core 5	14249	280418	30621	6264	3.5
Core 5	14257	281789	30804	6252	3.8
Core 5	14198	279734	30768	6234	3.8
Core 5	14226	286586	30640	6260	3.7
Core 5	14226	269244	30401	6238	4.0
Core 5	14230	282978	30699	6241	3.7
Core 5	14174	276467	30051	6330	3.7
Core 5	14210	292501	30866	6317	3.5
Core 5	14226	287743	30958	6299	3.2
Core 5	14230	289856	31065	6315	3.5
Core 5	14142	417482	50000	6643	21.8
Core 5	14214	282972	31655	6472	3.2
Core 5	14226	290171	31507	6435	3.2
Core 5	10809	284780	31772	6612	3.1
Core 5	5256	271019	34488	6911	3.9
MDD	13832	264136	29195	5850	3.3
MDD	13848	255654	31030	6236	3.2
MDD	13789	259708	30957	6413	2.8
MDD	10623	243158	34590	6860	3.5
MDD	5172	231660	40830	7123	4.7
MDD	5160	230345	40572	7374	4.2
MDD	13570	251464	29062	5973	2.5
MDD	13602	242280	30742	6424	2.2
MDD	10491	239663	33136	6752	2.5
MDD	5176	233370	39208	7308	3.3
MDD	5097	233972	38507	7250	3.3
MDD	13372	271351	31100	5529	1.5
MDD	10245	213776	35043	5820	1.1

Table B-6. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 100 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	243418	36211	6769	1.2
MDD	13487	239741	27553	5434	2.4
MDD	10253	243940	29291	6154	2.7
MDD	4906	341469	28769	6663	3.4
MDD	13229	285663	26446	5487	2.2
MDD	13284	280978	27284	5772	2.5
MDD	10146	286492	27114	5867	2.8
MDD	5073	331354	28585	6510	4.1
Core 4	13916	339058	25492	5771	2.3
Core 4	14079	362254	27360	6086	1.8
Core 4	10813	381400	27883	6526	2.2
Core 4	5283	420998	30137	7288	2.4
Core 3	14102	301455	27543	5764	1.9
Core 3	10873	308196	30468	5822	1.5
Core 3	5303	304829	32945	7211	3.6
Core 2	14099	251390	24065	4989	2.5
Core 2	10849	246757	30291	6188	2.5
Core 2	5268	219166	37608	7562	3.2
Core 1	13427	319619	21719	5019	2.2
Core 1	13530	323351	24410	5459	2.2
Core 1	10718	340026	27899	5713	3.6
Shear Slot	5204	321490	32331	6681	4.0
Shear Slot	13336	292599	23157	4889	1.7
Shear Slot	13435	286329	28574	5796	1.8
Shear Slot	10360	313480	30745	6267	1.6
Shear Slot	10380	319358	30703	6297	1.6
Shear Slot	13864	256533	27491	5701	1.7
Shear Slot	10774	256370	33060	6925	2.1

Table B-7. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 1000 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Unknown	4874	330095	35577	4187	8.2
Unknown	4926	327549	41472	4516	7.8
Unknown	4926	314500	44277	4398	7.9
Unknown	4974	314851	42838	4246	9.4
Unknown	10777	298319	35518	5641	2.1
Unknown	10821	289873	45301	5641	2.0
Unknown	10849	285892	43001	5692	2.1
Unknown	10881	290028	44705	5685	2.1
Unknown	10789	283431	44449	5525	1.8
Unknown	10809	305595	45791	5523	1.7
Unknown	10813	295231	46108	5548	2.3
Unknown	10837	295808	45755	5529	1.6
Unknown	10762	310716	44958	5664	1.9
Unknown	10817	311370	45155	5712	1.8
Unknown	10825	305855	45163	5703	2.0
Unknown	10849	301710	43645	5741	1.4
Unknown	10805	294474	44831	5571	1.4
Unknown	10809	312162	45524	5603	1.7
Unknown	10809	304786	45383	5593	2.0
Unknown	10849	310866	45761	5618	1.7
Unknown	10793	313775	45453	5658	1.8
Unknown	10805	310990	45518	5640	1.8
Unknown	10817	305522	45293	5658	1.8
Unknown	10833	293161	44592	5624	1.9
Core 5	5152	224682	43904	5325	6.4
Core 5	5156	225411	44418	5364	6.7
Core 5	9300	235791	40921	4947	5.7
Core 5	9379	236974	41233	4998	5.8
Core 5	10809	230271	40182	4834	5.6
Core 5	10817	232463	40356	4857	5.5
Core 5	14055	247790	30375	4843	4.6
Core 5	14138	233829	37158	4801	5.3
Core 5	5033	225235	43018	5362	6.1
Core 5	5093	231805	43622	5460	6.5

Table B-7. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 1000 ksi-PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 5	9268	240942	40409	5080	5.5
Core 5	9304	242185	40474	5073	5.4
Core 5	10718	236909	39635	4924	5.2
Core 5	10770	238001	40136	4951	5.1
Core 5	14178	236529	37819	4888	5.1
Core 5	14194	241791	38671	4879	5.0
Core 4	5033	310847	39453	5811	3.4
Core 4	5045	317922	38353	5896	3.3
Core 4	9153	316936	35841	5267	2.8
Core 4	9165	319968	35644	5315	2.7
Core 4	10631	308442	35315	5119	2.7
Core 4	10730	310274	35404	5161	2.7
Core 4	13956	309451	29200	4839	2.6
Core 4	14039	305359	33650	4952	2.6
Core 4	5001	306336	38902	5763	3.3
Core 4	5073	319150	38256	5873	3.2
Core 4	9113	326503	35215	5261	2.6
Core 4	9137	324722	35447	5255	2.6
Core 4	10627	319244	35151	5097	2.5
Core 4	10634	317659	34951	5098	2.5
Core 4	14134	310247	34257	4971	2.5
Core 4	14138	317550	34758	4956	2.5
Core 3	5029	253486	40748	5809	3.7
Core 3	5057	269483	39863	5871	3.5
Core 3	9133	275513	35724	5209	2.9
Core 3	9244	277545	36235	5203	2.8
Core 3	10722	275165	35369	5073	2.8
Core 3	10726	268229	35554	5032	3.0
Core 3	13892	265737	28885	4689	2.7
Core 3	14015	254953	33570	4812	2.8
Core 3	5081	268186	39602	5843	3.5
Core 3	5081	261281	39933	5801	3.5
Core 3	9141	283192	35876	5158	2.8
Core 3	9188	286368	35710	5163	2.9

Table B-7. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 1000 ksi-PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10698	284022	35282	5023	2.7
Core 3	10726	270604	35619	5018	2.6
Core 3	13979	261923	33648	4810	2.7
Core 3	14118	269273	34632	4819	2.4
Core 5	14142	215027	36259	5015	5.4
Core 5	14202	217204	38807	4939	5.3
Core 5	14249	217501	38935	4957	5.1
Core 5	14257	219869	39060	4949	5.3
Core 5	14198	218514	38967	4940	5.3
Core 5	14226	222674	38945	4954	5.2
Core 5	14226	211416	38444	4948	5.6
Core 5	14230	221081	38956	4942	5.2
Core 5	14174	214990	38152	5034	5.2
Core 5	14210	225936	39243	5015	4.9
Core 5	14226	221921	39330	5004	4.7
Core 5	14230	224111	39452	5014	5.0
Core 5	14142	100000	101626	4963	19.5
Core 5	14214	216918	40157	5168	4.6
Core 5	14226	221293	40102	5129	4.6
Core 5	10809	218068	40454	5261	4.6
Core 5	5256	207123	44586	5320	5.7
MDD	13832	206264	36495	4734	4.6
MDD	13848	200893	38508	5077	4.6
MDD	13789	202851	38471	5243	4.1
MDD	10623	182341	43500	5583	4.4
MDD	5172	179754	51177	5635	6.2
MDD	5160	176047	51268	5829	5.6
MDD	13570	196907	35746	4962	3.6
MDD	13602	189119	37740	5355	3.4
MDD	10491	187080	40661	5608	3.7
MDD	5176	177133	49331	5852	4.6
MDD	5097	179136	48301	5814	4.7
MDD	13372	168712	37756	4634	2.3
MDD	10245	166057	42519	4842	2.1

Table B-7. October 1991 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 1000 ksi-PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	4942	184713	45295	5476	2.6
MDD	13487	190429	33589	4532	3.5
MDD	10253	194501	35700	5144	3.9
MDD	4906	271593	36241	5413	4.6
MDD	13229	229948	32299	4579	3.2
MDD	13284	227089	33207	4831	3.5
MDD	10146	233362	32992	4904	3.8
MDD	5073	268133	35605	5308	5.2
Core 4	13916	260355	32525	4717	3.2
Core 4	14079	271374	35150	4979	2.6
Core 4	10813	280509	36425	5296	2.9
Core 4	5283	312360	40149	5720	3.6
Core 3	14102	225186	34793	4765	2.5
Core 3	10873	226808	38864	4701	2.2
Core 3	5303	234914	42139	5716	5.1
Core 2	14099	195901	29823	4144	3.4
Core 2	10849	189325	37764	5073	3.6
Core 2	5268	162962	48032	6030	4.3
Core 1	13427	254479	27321	4150	3.2
Core 1	13530	255163	30503	4534	3.1
Core 1	10718	269080	34996	4633	4.7
Shear Slot	5204	248987	41638	5192	5.6
Shear Slot	13336	227542	28833	4086	2.5
Shear Slot	13435	220203	35385	4830	2.6
Shear Slot	10360	238161	38492	5166	2.6
Shear Slot	10380	243357	38390	5201	2.5
Shear Slot	13864	191566	34948	4621	2.7
Shear Slot	10774	191076	41901	5617	3.1

APPENDIX C

JUNE 1992 WSDOT FWD DEFLECTION DATA—
PACCAR TEST SECTION

Table C-1. June 1992 WSDOT FWD Deflection Data - PACCAR Test Section

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
MDD	5415	16.27	10.42	8.34	4.20	2.20	1.18
MDD	5490	15.21	9.96	8.00	4.12	2.19	1.20
MDD	5466	14.63	10.02	7.98	4.09	2.17	1.20
MDD	5478	14.11	9.81	7.85	4.06	2.19	1.22
MDD	5510	14.52	10.00	7.99	4.11	2.19	1.21
MDD	5542	14.19	9.75	7.83	4.05	2.17	1.22
MDD	5498	15.50	9.94	7.92	4.10	2.19	1.23
MDD	5470	15.24	9.67	7.73	4.01	2.16	1.22
MDD	9447	25.43	17.61	14.22	7.48	3.96	2.13
MDD	9506	23.74	17.00	13.79	7.36	4.00	2.19
MDD	9435	24.69	17.35	14.09	7.42	4.02	2.21
MDD	9478	23.83	16.90	13.80	7.35	4.02	2.20
MDD	9391	24.61	17.25	13.97	7.37	3.99	2.19
MDD	9486	23.72	16.85	13.71	7.33	4.00	2.20
MDD	9387	24.81	17.14	13.85	7.35	4.00	2.19
MDD	9451	23.80	16.80	13.66	7.35	4.01	2.22
MDD	9399	24.47	17.09	13.83	7.32	3.97	2.17
MDD	9467	23.43	16.75	13.62	7.29	3.98	2.20
MDD	9399	23.84	17.02	13.79	7.29	3.94	2.17
MDD	9498	23.27	16.77	13.66	7.30	3.98	2.20
MDD	10869	27.76	19.60	15.94	8.51	4.66	2.55
MDD	10932	26.93	19.12	15.64	8.43	4.63	2.55
MDD	10833	27.72	19.54	15.88	8.49	4.63	2.56
MDD	10920	27.04	19.07	15.58	8.42	4.60	2.56
MDD	10742	28.03	19.59	15.91	8.48	4.63	2.54
MDD	10849	27.38	19.13	15.63	8.44	4.64	2.57
Core 4	5363	10.35	8.01	6.79	3.69	1.87	0.98
Core 4	5395	9.65	7.79	6.61	3.67	1.89	1.00
Core 4	5339	9.94	7.81	6.66	3.64	1.89	0.99
Core 4	5339	9.77	7.65	6.51	3.60	1.86	1.00
Core 4	5351	9.85	7.67	6.52	3.62	1.87	0.99
Core 4	5411	9.85	7.69	6.54	3.61	1.86	0.99
Core 4	5359	10.04	7.71	6.56	3.63	1.89	1.02
Core 4	5367	9.90	7.64	6.50	3.61	1.87	1.00
Core 4	9538	17.88	15.24	13.06	7.32	3.84	2.00

Table C-1. June 1992 WSDOT FWD Deflection Data - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
Core 4	9514	17.14	14.80	12.71	7.22	3.84	2.04
Core 4	9542	17.48	14.94	12.83	7.27	3.87	2.06
Core 4	9538	17.24	14.74	12.68	7.24	3.89	2.06
Core 4	9542	17.59	14.93	12.82	7.29	3.87	2.05
Core 4	9510	17.31	14.69	12.63	7.21	3.87	2.04
Core 4	9482	17.51	14.84	12.72	7.21	3.83	2.03
Core 4	9542	17.28	14.73	12.66	7.24	3.91	2.07
Core 4	10984	20.72	17.40	14.93	8.52	4.54	2.39
Core 4	10960	20.71	17.19	14.77	8.48	4.56	2.42
Core 4	11071	20.79	17.37	14.93	8.53	4.56	2.43
Core 4	11091	20.94	17.27	14.86	8.55	4.59	2.44
Core 4	11000	21.15	17.41	14.96	8.56	4.58	2.42
Core 4	10968	20.72	17.23	14.83	8.53	4.60	2.44
Core 4	11028	21.06	17.41	14.97	8.56	4.61	2.45
Core 4	11040	20.74	17.21	14.81	8.54	4.53	2.47
Core 4	11064	20.98	17.37	14.92	8.53	4.58	2.43
Core 4	11083	20.86	17.25	14.85	8.56	4.64	2.47
Core 3	5323	8.72	7.92	6.71	3.74	1.89	1.02
Core 3	5260	8.10	7.67	6.49	3.63	1.86	1.02
Core 3	5307	5.76	7.73	6.54	3.60	1.88	0.99
Core 3	5299	7.88	7.66	6.49	3.59	1.87	1.00
Core 3	5395	8.72	7.86	6.65	3.64	1.89	1.00
Core 3	5295	8.41	7.59	6.41	3.52	1.81	0.94
Core 3	9506	19.67	15.48	13.25	7.44	3.90	2.02
Core 3	9494	19.27	15.09	12.94	7.31	3.85	2.03
Core 3	9494	19.57	15.24	13.03	7.32	3.87	2.03
Core 3	9514	19.42	15.08	12.92	7.30	3.85	2.02
Core 3	9494	19.50	15.23	13.03	7.31	3.84	2.02
Core 3	9490	18.33	15.06	12.90	7.28	3.83	2.02
Core 3	9494	19.74	15.21	13.03	7.31	3.89	2.03
Core 3	9471	18.32	14.97	12.85	7.27	3.88	2.01
Core 3	11012	22.07	17.82	15.26	8.61	4.58	2.39
Core 3	11012	21.51	17.63	15.13	8.59	4.59	2.41
Core 3	10952	21.63	17.85	15.27	8.65	4.60	2.42

Table C-1. June 1992 WSDOT FWD Deflection Data - PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
Core 3	10920	21.31	17.63	15.14	8.59	4.59	2.43
Core 3	10940	22.15	17.88	15.31	8.70	4.65	2.43
Core 3	10920	21.68	17.64	15.14	8.61	4.60	2.42
Core 3	10936	21.98	17.81	15.24	8.61	4.60	2.41
Core 3	11004	21.84	17.63	15.13	8.59	4.60	2.42
Core 3	10889	21.95	17.83	15.27	8.63	4.61	2.42
Core 3	10873	21.65	17.59	15.09	8.59	4.59	2.41

APPENDIX D

JUNE 1992 WSDOT FWD TESTING EVERCALC OUTPUT—PACCAR TEST SECTION

Table D-1. June 1992 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
MDD	5415	94943	25063	7956	1.8
MDD	5490	108116	27452	8192	1.7
MDD	5466	135531	25163	8573	1.2
MDD	5478	145270	26432	8546	1.0
MDD	5510	142147	25234	8661	1.1
MDD	5542	142678	26728	8805	1.3
MDD	5470	93553	28517	8993	1.7
MDD	5498	97457	27217	8872	1.7
MDD	9447	146676	25014	7874	1.5
MDD	9506	172183	26932	7892	1.1
MDD	9435	150822	26495	7773	1.2
MDD	9478	165698	27265	7902	1.2
MDD	9391	149087	26459	7849	1.2
MDD	9486	166259	27387	7984	1.2
MDD	9387	137251	27258	7904	1.3
MDD	9451	158264	27927	7950	1.3
MDD	9399	147703	26931	7886	1.2
MDD	9467	170359	27650	7949	1.1
MDD	9399	168902	26023	8034	1.1
MDD	9498	181872	26950	8078	1.1
MDD	10869	157351	27239	7861	1.2
MDD	10932	169032	28164	8003	1.3
MDD	10833	156686	27003	8013	1.2
MDD	10920	163789	28134	8175	1.4
MDD	10742	146504	27234	7806	1.2
MDD	10849	149696	28966	7892	1.4
Core 4	5363	519715	17701	10673	1.6
Core 4	5395	630037	17411	10857	1.0
Core 4	5339	569719	17825	10737	1.3
Core 4	5339	554568	19507	10747	1.5
Core 4	5351	565749	18878	10766	1.7
Core 4	5411	569566	18878	10998	1.6
Core 4	5359	500163	20913	10588	1.8
Core 4	5367	543014	19595	10938	1.9

Table D-1. June 1992 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 4	9514	742309	16055	8844	0.9
Core 4	9538	696805	15083	8906	0.8
Core 4	9538	745259	15976	9038	0.5
Core 4	9542	706407	16297	8975	0.8
Core 4	9510	730995	16162	8999	0.5
Core 4	9542	704030	16217	8933	0.7
Core 4	9482	689814	16486	8969	0.6
Core 4	9542	732722	16580	8902	0.4
Core 4	10960	647273	18209	8479	0.8
Core 4	10984	674337	16598	8665	0.6
Core 4	11071	658587	17449	8750	0.7
Core 4	11091	658587	17449	8750	1.0
Core 4	10968	656095	17885	8507	0.8
Core 4	11000	628273	17775	8556	0.9
Core 4	11028	656095	17885	8507	1.0
Core 4	11040	648564	18652	8489	0.8
Core 4	11064	635943	18034	8632	0.8
Core 4	11083	644176	18709	8499	0.9
Core 3	5260	971186	12800	11020	3.7
Core 3	5323	862646	13133	10760	2.8
Core 3	5299	1000000	12196	11752	4.2
Core 3	5307	1000000	24808	10753	15.7
Core 3	5295	921728	11592	12183	2.2
Core 3	5395	857205	13580	11141	2.3
Core 3	9494	496325	19947	8515	1.8
Core 3	9506	508182	18278	8484	1.7
Core 3	9494	471871	20084	8507	1.8
Core 3	9514	486701	19983	8620	2.0
Core 3	9490	602119	17793	8785	0.9
Core 3	9494	479829	19722	8581	1.7
Core 3	9471	621852	17195	8715	1.0
Core 3	9494	449931	20935	8350	2.0
Core 3	11012	595377	18127	8398	0.9
Core 3	11012	553588	18309	8380	1.1

Table D-1. June 1992 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 50 ksi- PACCAR Test Section (cont.)

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 3	10920	599132	18114	8280	0.8
Core 3	10952	588722	17720	8301	0.8
Core 3	10920	571346	18476	8265	1.1
Core 3	10940	546693	18577	8158	1.2
Core 3	10936	547111	18618	8257	1.0
Core 3	11004	555571	19066	8327	1.2
Core 3	10873	569284	18480	8233	1.1
Core 3	10889	546263	18634	8157	1.0

APPENDIX E

FEBRUARY 1993 WSDOT FWD DEFLECTION DATA—PACCAR TEST SECTION

Table E-1. February 1993 WSDOT FWD Deflection Data - PACCAR Test Section

STATION NUMBER	LOAD (pounds)	DEFLECTION (Sensor spacing and mils)					
		0 in.	8 in.	12 in.	24 in.	36 in.	48 in.
Core 1	6054	7.74	6.80	6.10	3.94	2.41	1.42
Core 1	6205	7.98	6.99	6.27	4.04	2.47	1.45
Core 1	6356	8.09	7.10	6.35	4.10	2.50	1.50
Core 1	10646	13.75	12.30	11.10	7.30	4.50	2.67
Core 1	10777	14.04	12.49	11.27	7.42	4.56	2.70
Core 1	10837	14.14	12.61	11.37	7.48	4.61	2.73
Core 1	17594	22.45	19.97	18.09	11.98	7.40	4.35
Core 1	17614	22.52	20.05	18.15	12.05	7.45	4.37
Core 1	17634	22.44	19.99	18.13	12.02	7.46	4.38
Core 5	6050	7.13	6.03	5.39	3.48	2.11	1.27
Core 5	6118	7.09	5.98	5.32	3.43	2.08	1.26
Core 5	6173	7.03	5.93	5.30	3.42	2.09	1.25
Core 5	10515	12.43	10.65	9.54	6.23	3.83	2.30
Core 5	10543	12.17	10.41	9.32	6.09	3.73	2.26
Core 5	10631	12.32	10.54	9.46	6.17	3.79	2.30
Core 5	17813	20.17	17.22	15.50	10.19	6.31	3.77
Core 5	17868	20.06	17.08	15.35	10.09	6.26	3.74
Core 5	17880	19.97	17.04	15.30	10.07	6.26	3.74

APPENDIX F

FEBRUARY 1993 WSDOT FWD TESTING EVERCALC OUTPUT— PACCAR TEST SECTION

Table F-1. February 1993 WSDOT FWD Testing EVERCALC Output With Stiff Layer Modulus at 40 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 1	6205	1756939	11883	14051	1.0
Core 1	6054	1756939	11883	14051	0.9
Core 1	6356	1658151	14671	13570	0.6
Core 1	10777	1898220	10483	13065	0.8
Core 1	10837	1898220	10483	13065	0.7
Core 1	10646	1898220	10483	13065	0.7
Core 1	17594	2000001	8893	14138	0.7
Core 1	17614	2000001	8893	14138	0.8
Core 1	17634	2000001	8893	14138	0.8
Core 5	6050	1745537	14840	17121	1.3
Core 5	6118	1701686	16490	17428	1.3
Core 5	6173	1892200	13157	18956	1.4
Core 5	10515	1869770	13541	16383	1.2
Core 5	10543	1836534	15441	16387	1.2
Core 5	10631	1868311	14658	16831	1.2
Core 5	17813	2194255	9644	19617	1.4
Core 5	17868	2204032	9823	19967	1.5
Core 5	17880	2232812	9658	20177	1.5

Table F-2. February 1993 WSDOT FWD Testing EVERCALC Output
With Stiff Layer Modulus at 50 ksi- PACCAR Test Section

STATION NUMBER	LOAD (pounds)	LAYER MODULI (psi)			RMS ERROR
		AC	BASE	SUBGRADE	
Core 1	6205	1364415	23896	11002	1.0
Core 1	6054	1364415	23896	11002	1.0
Core 1	6356	1351816	25614	10981	0.7
Core 1	10777	1554354	21037	10196	1.0
Core 1	10837	1554354	21037	10196	1.0
Core 1	10646	1554354	21037	10196	0.8
Core 1	17594	1772724	16297	10875	1.0
Core 1	17614	1832288	14815	10998	1.0
Core 1	17634	1832286	15302	10939	1.0
Core 5	6050	1381121	28046	13320	1.5
Core 5	6118	1339498	30189	13681	1.5
Core 5	6173	1478742	27261	14172	1.6
Core 5	10515	1462641	27383	12601	1.4
Core 5	10543	1471602	28619	13035	1.4
Core 5	10631	1446354	29421	12825	1.4
Core 5	17813	1671205	24908	13514	1.7
Core 5	17868	1662647	25680	13713	1.7
Core 5	17880	1679038	25737	13742	1.7

APPENDIX G

SAMPLE CHEVPC OUTPUT FOR OCTOBER 1991 FWD TESTING— PACCAR TEST SECTION

Table G-1. Calculated Strains for Axial Core 1 at FWD Drop Height 1, October 1991 Testing—PACCAR Test Section

```
OCT FWD TESTING CORE 1                                                    PAGE 1

              THE PROBLEM PARAMETERS ARE
TOTAL LOAD:    5109.00  LBS          TIRE PRESSURE:       46.72  PSI
LOAD RADIUS:      5.90  IN.

LAYER 1 HAS MODULUS  500000. POISSONS RATIO 0.350 AND THICKNESS  0.40 IN,
LAYER 2 HAS MODULUS  562823. POISSONS RATIO 0.350 AND THICKNESS  4.90 IN,
LAYER 3 HAS MODULUS  500000. POISSONS RATIO 0.350 AND THICKNESS  0.40 IN,
LAYER 4 HAS MODULUS   14771. POISSONS RATIO 0.400 AND THICKNESS 12.70 IN,
LAYER 5 HAS MODULUS   10158. POISSONS RATIO 0.450 AND THICKNESS 42.70 IN,
LAYER 6 HAS MODULUS   40000. POISSONS RATIO 0.350 AND IS SEMI-INFINITE.
```

LOCATION R	LOCATION Z	S-T-R-E-S-S-E-S PSI VERTICAL	TANGENTIAL	RADIAL	SHEAR	DEFLECTION INCHES VERTICAL	S-T-R-A-I-N-S MICROINCHES/INCH VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	ANGLE DEG WITH R AXIS
0.00	-0.40	-36.9016	-103.8851	-103.8851	0.0000	0.009763	71.64	-109.22	-109.22	0.00	71.64	V DIR
0.00	0.40	-36.9016	-114.4413	-114.4413	0.0000	0.009763	76.77	-109.22	-109.22	0.00	76.77	V DIR
0.00	-5.30	-8.2213	99.4926	99.4926	0.0000	0.009589	-138.35	120.02	120.02	0.00	120.02	TR
0.00	5.30	-8.2213	87.8929	87.8929	0.0000	0.009589	-139.49	120.02	120.02	0.00	120.02	TR

Table G-2. Calculated Strains for Axial Core 3 at FWD Drop Height 1, October 1991 Testing—PACCAR Test Section

OCT FWD TESTING CORE 3 PAGE 1

THE PROBLEM PARAMETERS ARE

TOTAL LOAD: 5110.00 LBS TIRE PRESSURE: 46.73 PSI

LOAD RADIUS: 5.90 IN.

LAYER 1 HAS MODULUS 500000. POISSONS RATIO 0.350 AND THICKNESS 0.25 IN.

LAYER 2 HAS MODULUS 562823. POISSONS RATIO 0.350 AND THICKNESS 4.90 IN.

LAYER 3 HAS MODULUS 500000. POISSONS RATIO 0.350 AND THICKNESS 1.25 IN.

LAYER 4 HAS MODULUS 14771. POISSONS RATIO 0.400 AND THICKNESS 12.00 IN.

LAYER 5 HAS MODULUS 10158. POISSONS RATIO 0.450 AND THICKNESS 46.00 IN.

LAYER 6 HAS MODULUS 40000. POISSONS RATIO 0.350 AND IS SEMI-INFINITE.

LOCATION		S-T-R-E-S-S-E-S PSI				DEFLECTION INCHES	S-T-R-A-I-N-S MICROINCHES/INCH					ANGLE DEG
R	Z	VERTICAL	TANGENTIAL	RADIAL	SHEAR	VERTICAL	VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	WITH R AXIS
0.00	-0.25	-42.7829	-101.0804	-101.0804	0.0000	0.008852	55.95	-101.46	-101.46	0.00	55.95	V DIR
0.00	0.25	-42.7829	-110.8862	-110.8862	0.0000	0.008852	61.90	-101.46	-101.46	0.00	61.90	V DIR
0.00	-5.15	-11.1446	59.8100	59.8100	0.0000	0.008724	-94.19	76.00	76.00	0.00	76.00	TR
0.00	5.15	-11.1446	52.4641	52.4641	0.0000	0.008724	-95.74	76.00	76.00	0.00	76.00	TR

Table G-3. Calculated Strains for Axial Core 4 at FWD Drop Height 1, October 1991 Testing—PACCAR Test Section

```
OCT FWD TESTING CORE 4                                              PAGE  1

              THE PROBLEM PARAMETERS ARE
TOTAL LOAD:       5268.00  LBS            TIRE PRESSURE:       48.17  PSI
LOAD RADIUS:         5.90  IN.

LAYER  1  HAS MODULUS   562823.  POISSONS RATIO 0.350  AND THICKNESS   4.90 IN.
LAYER  2  HAS MODULUS   500000.  POISSONS RATIO 0.350  AND THICKNESS   0.50 IN.
LAYER  3  HAS MODULUS    14771.  POISSONS RATIO 0.400  AND THICKNESS  13.00 IN.
LAYER  4  HAS MODULUS    10158.  POISSONS RATIO 0.450  AND THICKNESS  46.10 IN.
LAYER  5  HAS MODULUS    40000.  POISSONS RATIO 0.350  AND IS SEMI-INFINITE.
```

LOCATION R	LOCATION Z	S-T-R-E-S-S-E-S PSI VERTICAL	TANGENTIAL	RADIAL	SHEAR	DEFLECTION INCHES VERTICAL	S-T-R-A-I-N-S MICROINCHES/INCH VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	ANGLE DEG WITH R AXIS
0.00	0.00	-48.1700	-149.1831	-149.1831	0.0000	0.010608	99.96	-142.34	-142.34	0.00	99.96	V DIR S
0.00	-4.90	-9.5734	102.8243	102.8243	0.0000	0.010464	-144.90	124.70	124.70	0.00	124.70	TR
0.00	4.90	-9.5734	90.7715	90.7715	0.0000	0.010464	-146.23	124.70	124.70	0.00	124.70	TR

Table G-4. Calculated Strains for Axial Core 5 at FWD Drop Height 1, October 1991 Testing—PACCAR Test Section

OCT FWD TESTING CORE 5 PAGE 1

THE PROBLEM PARAMETERS ARE

TOTAL LOAD: 5204.00 LBS TIRE PRESSURE: 47.59 PSI

LOAD RADIUS: 5.90 IN.

LAYER 1 HAS MODULUS 500000. POISSONS RATIO 0.350 AND THICKNESS 0.60 IN,
LAYER 2 HAS MODULUS 562823. POISSONS RATIO 0.350 AND THICKNESS 4.90 IN,
LAYER 3 HAS MODULUS 500000. POISSONS RATIO 0.350 AND THICKNESS 0.60 IN,
LAYER 4 HAS MODULUS 14771. POISSONS RATIO 0.400 AND THICKNESS 12.30 IN,
LAYER 5 HAS MODULUS 10158. POISSONS RATIO 0.450 AND THICKNESS 43.80 IN,
LAYER 6 HAS MODULUS 40000. POISSONS RATIO 0.350 AND IS SEMI-INFINITE.

LOCATION		S-T-R-E-S-S-E-S PSI				DEFLECTION INCHES	S-T-R-A-I-N-S MICROINCHES/INCH					ANGLE DEG
R	Z	VERTICAL	TANGENTIAL	RADIAL	SHEAR	VERTICAL	VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	WITH R AXIS
0.00	-0.60	-38.0388	-93.5620	-93.5620	0.0000	0.009394	54.91	-95.00	-95.00	0.00	54.91	V DIR
0.00	0.60	-38.0388	-102.7442	-102.7442	0.0000	0.009394	60.20	-95.00	-95.00	0.00	60.20	V DIR
0.00	-5.50	-8.3004	86.9651	86.9651	0.0000	0.009211	-122.91	105.60	105.60	0.00	105.60	TR
0.00	5.50	-8.3004	76.7590	76.7590	0.0000	0.009211	-124.06	105.60	105.60	0.00	105.60	TR

APPENDIX H

SAMPLE CHEVPC OUTPUT FOR FEBRUARY 1993 FWD TESTING—PACCAR TEST SECTION

Table H-1. Calculated Strains for Axial Core 1 at FWD Drop Height 1, February 1993 Testing—PACCAR Test Section

```
FEB FWD TESTING CORE 1                                                    PAGE 1

                THE PROBLEM PARAMETERS ARE
TOTAL LOAD:      6205.00  LBS            TIRE PRESSURE:        56.70  PSI
LOAD RADIUS:        5.90  IN.

LAYER  1  HAS MODULUS   500000.  POISSONS RATIO 0.350  AND THICKNESS   0.40 IN,
LAYER  2  HAS MODULUS  1575667.  POISSONS RATIO 0.350  AND THICKNESS   4.90 IN,
LAYER  3  HAS MODULUS   500000.  POISSONS RATIO 0.350  AND THICKNESS   0.40 IN,
LAYER  4  HAS MODULUS    20326.  POISSONS RATIO 0.400  AND THICKNESS  12.70 IN,
LAYER  5  HAS MODULUS    10710.  POISSONS RATIO 0.450  AND THICKNESS  57.10 IN,
LAYER  6  HAS MODULUS    50000.  POISSONS RATIO 0.350  AND IS SEMI-INFINITE.
```

LOCATION		S-T-R-E-S-S-E-S PSI				*DEFLECTION* INCHES	S-T-R-A-I-N-S MICROINCHES/INCH					*ANG * DI
R	Z	VERTICAL	TANGENTIAL	RADIAL	SHEAR	VERTICAL	VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	WI R A
0.00	-0.40	-62.2205	-89.8717	-89.8717	0.0000	0.008169	1.38	-73.28	-73.28	0.00	1.38	V DIF
0.00	0.40	-62.2205	-211.1388	-211.1388	0.0000	0.008169	54.31	-73.28	-73.28	0.00	54.31	V DIR
0.00	-5.30	-7.0356	189.3184	189.3184	0.0000	0.008078	-88.57	79.66	79.66	0.00	79.66	TR
0.00	5.30	-7.0356	57.4894	57.4894	0.0000	0.008078	-94.56	79.66	79.66	0.00	79.66	TR

Table H-2. Calculated Strains for Axial Core 3 at FWD Drop Height 1, February 1993 Testing—PACCAR Test Section

```
FEB FWD TESTING CORE 3                                                PAGE  1

                THE PROBLEM PARAMETERS ARE
TOTAL LOAD:       6160.00  LBS             TIRE PRESSURE:        56.33  PSI
LOAD RADIUS:         5.90  IN.

LAYER  1  HAS MODULUS   500000.  POISSONS RATIO 0.350  AND THICKNESS   0.25 IN,
LAYER  2  HAS MODULUS  1510316.  POISSONS RATIO 0.350  AND THICKNESS   4.90 IN,
LAYER  3  HAS MODULUS   500000.  POISSONS RATIO 0.250  AND THICKNESS   1.25 IN,
LAYER  4  HAS MODULUS    27471.  POISSONS RATIO 0.400  AND THICKNESS  12.00 IN,
LAYER  5  HAS MODULUS    13400.  POISSONS RATIO 0.450  AND THICKNESS  60.40 IN,
LAYER  6  HAS MODULUS    50000.  POISSONS RATIO 0.350  AND IS SEMI-INFINITE.
```

LOCATION R	Z	S-T-R-E-S-S-E-S PSI VERTICAL	TANGENTIAL	RADIAL	SHEAR	DEFLECTION INCHES VERTICAL	S-T-R-A-I-N-S MICROINCHES/INCH VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	ANGLE DEG WITH R AXIS
0.00	-0.25	-71.8524	-89.5800	-89.5800	0.0000	0.006762	-18.29	-66.16	-66.16	0.00	-18.29	V DIR
0.00	0.25	-71.8524	-192.4104	-192.4104	0.0000	0.006762	41.60	-66.16	-66.16	0.00	41.60	V DIR
0.00	-5.15	-11.1163	135.5282	135.5282	0.0000	0.006674	-70.17	60.90	60.90	0.00	60.90	TR
0.00	5.15	-11.1163	35.8971	36.8971	0.0000	0.006674	-59.13	60.90	60.90	0.00	60.90	TR

Table H-3. Calculated Strains for Axial Core 4 at FWD Drop Height 1, February 1993 Testing—PACCAR Test Section

```
FEB FWD TESTING CORE 4                                                       PAGE  1

                 THE PROBLEM PARAMETERS ARE
TOTAL LOAD:      6160.00  LBS          TIRE PRESSURE:        56.33  PSI
LOAD RADIUS:        5.90  IN.

LAYER  1  HAS MODULUS  1510316.  POISSONS RATIO 0.350  AND THICKNESS   4.90 IN,
LAYER  2  HAS MODULUS   500000.  POISSONS RATIO 0.250  AND THICKNESS   0.50 IN,
LAYER  3  HAS MODULUS    27471.  POISSONS RATIO 0.400  AND THICKNESS  13.00 IN,
LAYER  4  HAS MODULUS    13400.  POISSONS RATIO 0.450  AND THICKNESS  60.50 IN,
LAYER  5  HAS MODULUS    50000.  POISSONS RATIO 0.350  AND IS SEMI-INFINITE.
```

LOCATION R	Z	S-T-R-E-S-S-E-S PSI VERTICAL	TANGENTIAL	RADIAL	SHEAR	DEFLECTION INCHES VERTICAL	S-T-R-A-I-N-S MICROINCHES/INCH VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	ANGLE DEG WITH R AXIS
0.00	0.00	-56.3301	-209.4268	-209.4268	0.0000	0.007308	59.77	-77.08	-77.08	0.00	59.77	V DIR S
0.00	-4.90	-9.0387	170.7696	170.7696	0.0000	0.007237	-85.13	75.59	75.59	0.00	75.59	TR
0.00	4.90	-9.0387	47.3800	47.3800	0.0000	0.007237	-65.46	75.59	75.59	0.00	75.59	TR

Table H-4. Calculated Strains for Axial Core 5 at FWD Drop Height 4, February 1993 Testing—PACCAR Test Section

FEB FWD TESTING CORE 5 PAGE 1

THE PROBLEM PARAMETERS ARE

TOTAL LOAD: 17853.00 LBS TIRE PRESSURE: 163.25 PSI

LOAD RADIUS: 5.90 IN.

LAYER 1 HAS MODULUS 500000. POISSONS RATIO 0.350 AND THICKNESS 0.60 IN,
LAYER 2 HAS MODULUS 1510316. POISSONS RATIO 0.350 AND THICKNESS 4.90 IN,
LAYER 3 HAS MODULUS 500000. POISSONS RATIO 0.350 AND THICKNESS 0.60 IN,
LAYER 4 HAS MODULUS 27471. POISSONS RATIO 0.400 AND THICKNESS 12.30 IN,
LAYER 5 HAS MODULUS 13400. POISSONS RATIO 0.450 AND THICKNESS 58.40 IN,
LAYER 6 HAS MODULUS 50000. POISSONS RATIO 0.350 AND IS SEMI-INFINITE.

LOCATION		S-T-R-E-S-S-E-S PSI				DEFLECTION INCHES	S-T-R-A-I-N-S MICROINCHES/INCH					ANGI DE
R	Z	VERTICAL	TANGENTIAL	RADIAL	SHEAR	VERTICAL	VERTICAL	TANGENTIAL	RADIAL	SHEAR IN MICRO RAD.	MAX.PRIN.IN TENSILE DIR.	WI R A
0.00	-0.60	-178.2620	-235.7055	-235.7055	0.0000	0.020115	-26.54	-181.63	-181.63	0.00	-26.54	V DIR
0.00	0.60	-178.2621	-518.0247	-518.0247	0.0000	0.020115	122.06	-181.63	-181.63	0.00	122.06	V DIR
0.00	-5.50	-24.5279	453.0211	453.0211	0.0000	0.019838	-226.21	200.65	200.65	0.00	200.65	TR
0.00	5.50	-24.5278	141.1407	141.1407	0.0000	0.019838	-246.65	200.65	200.65	0.00	200.65	TR

APPENDIX I

SAMPLE STRAIN-TIME PLOTS FOR OCTOBER 1991 FWD TESTING— PACCAR TEST SECTION

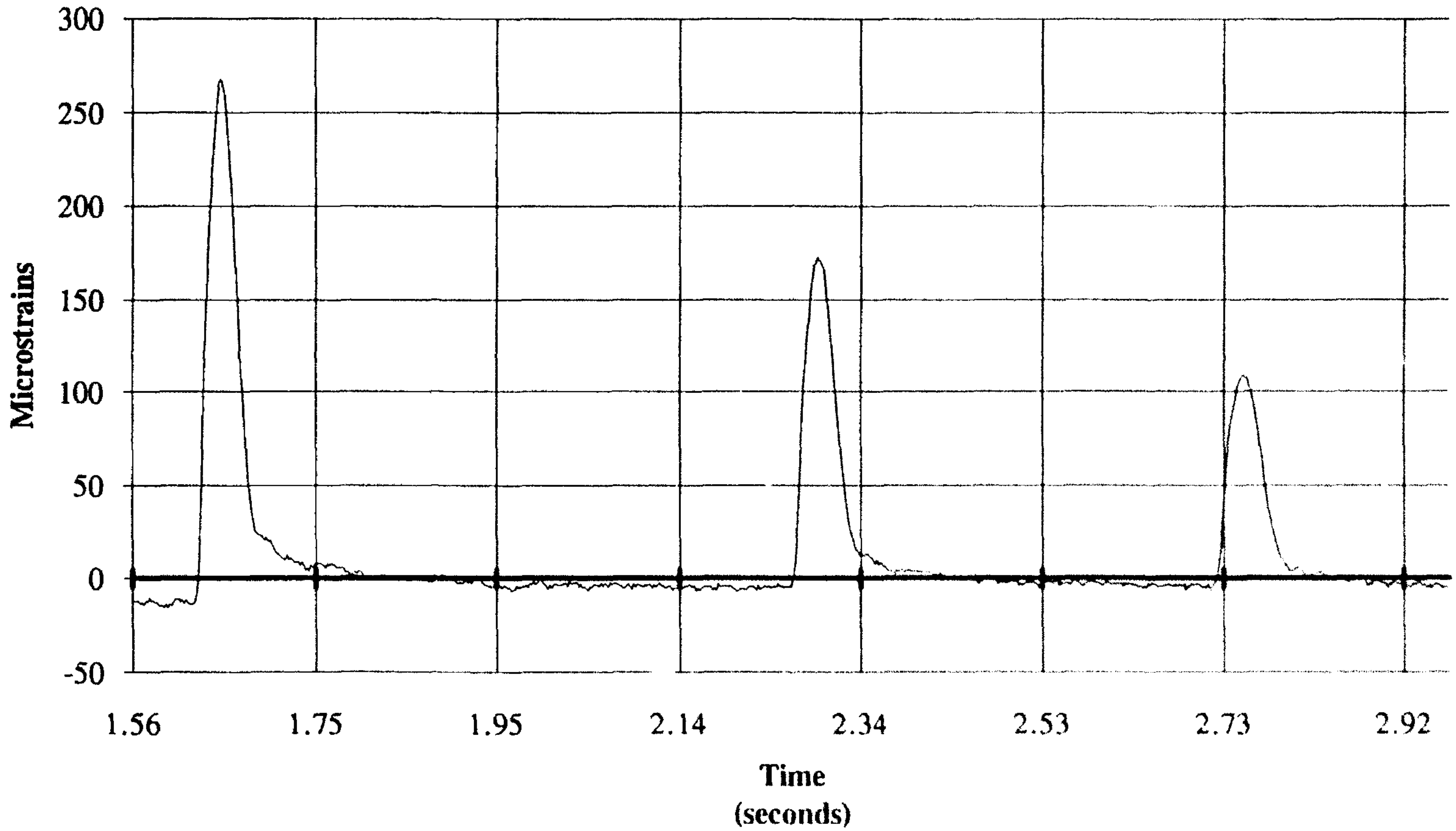

Figure I-1. Strain-Time Plot for Gauge 4BL, Drop Height 2, October 1991 FWD Testing—PACCAR Test Section

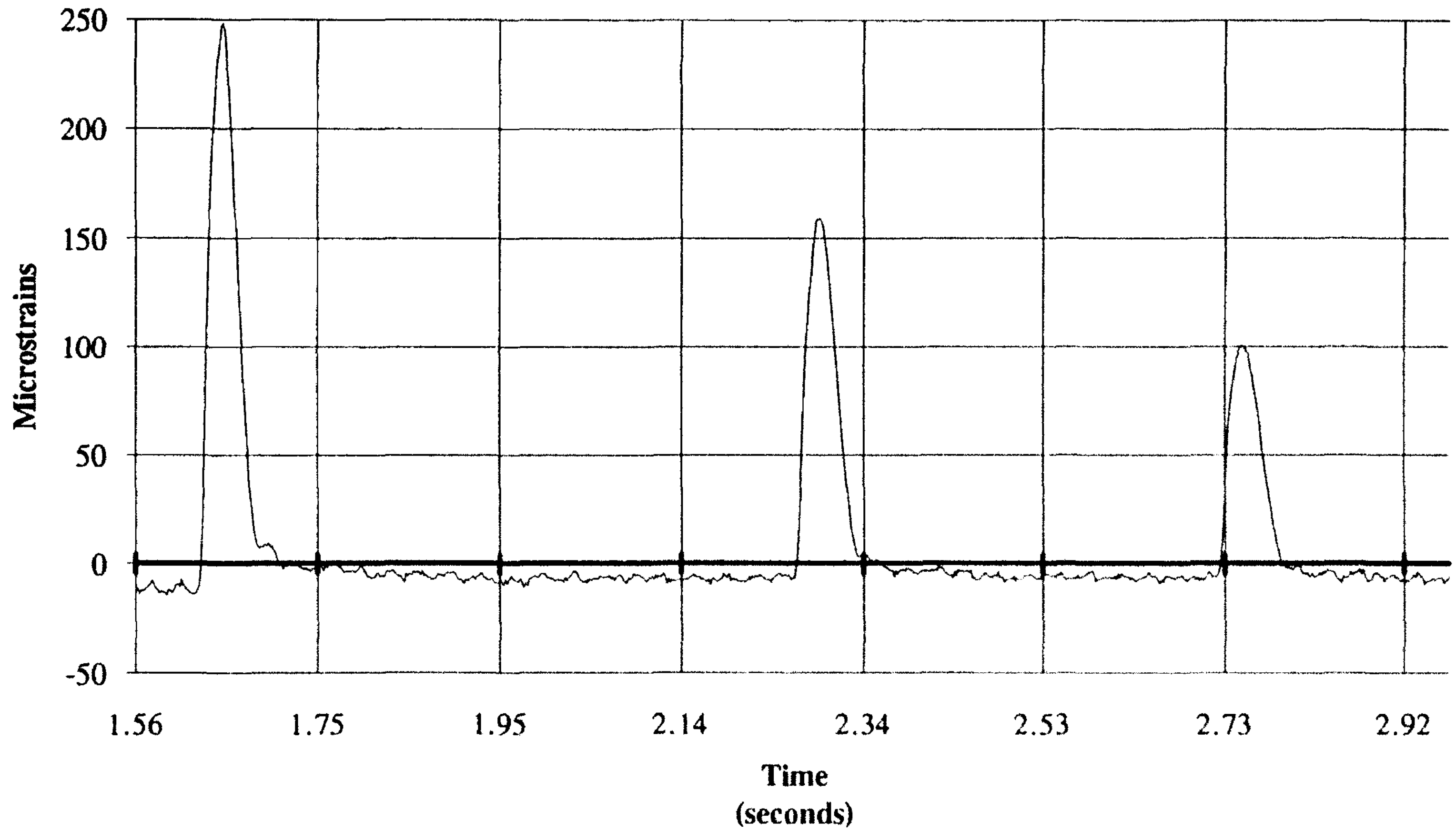

Figure I-2. Strain-Time Plot for Gauge 4BT, Drop Height 2, October 1991 FWD Testing—PACCAR Test Section

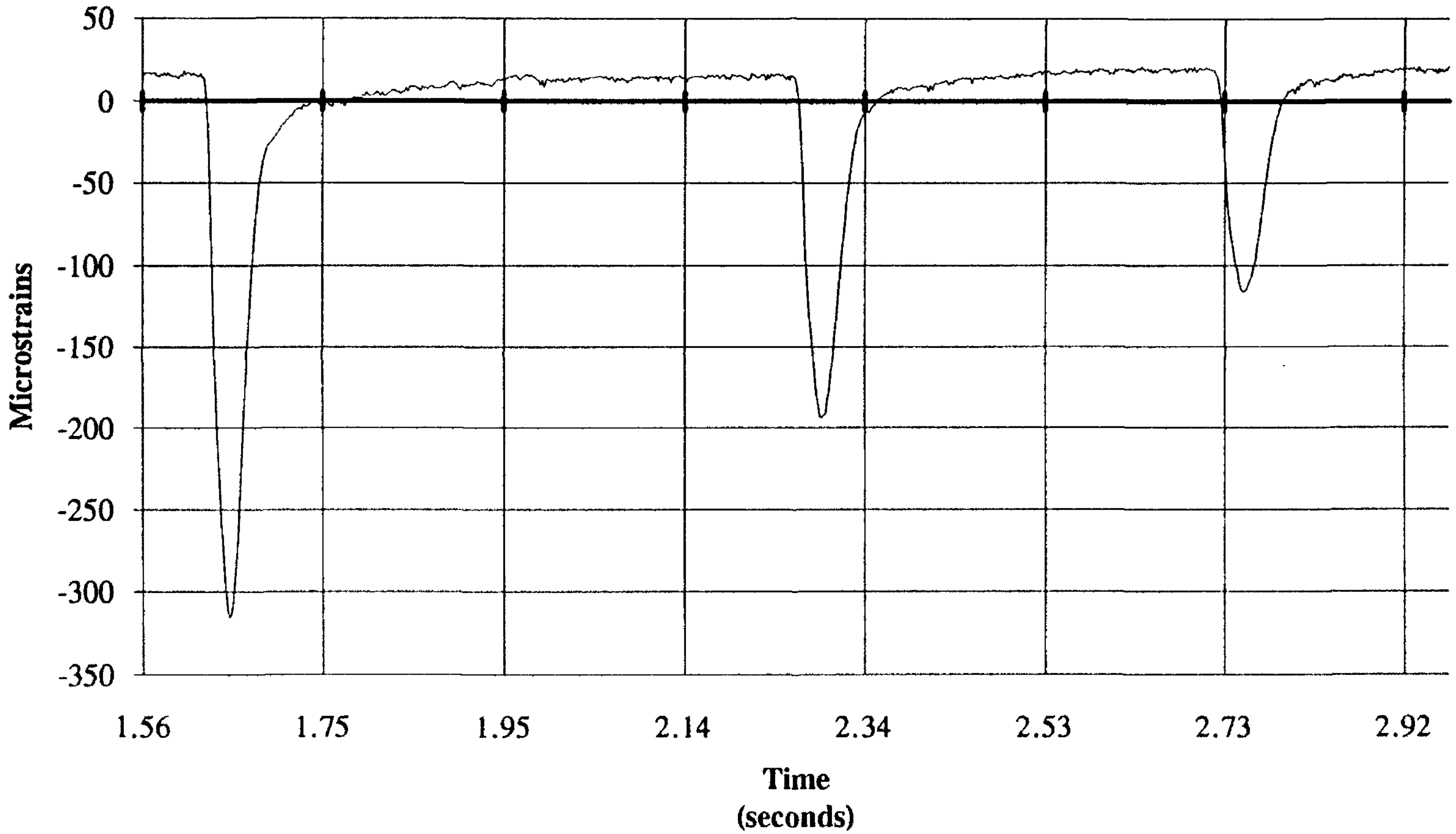

Figure I-3. Strain-Time Plot for Gauge 10SL, Drop Height 2, October 1991 FWD Testing—PACCAR Test Section

APPENDIX J

SAMPLE STRAIN-TIME PLOTS FOR FEBRUARY 1993 FWD TESTING—PACCAR TEST SECTION

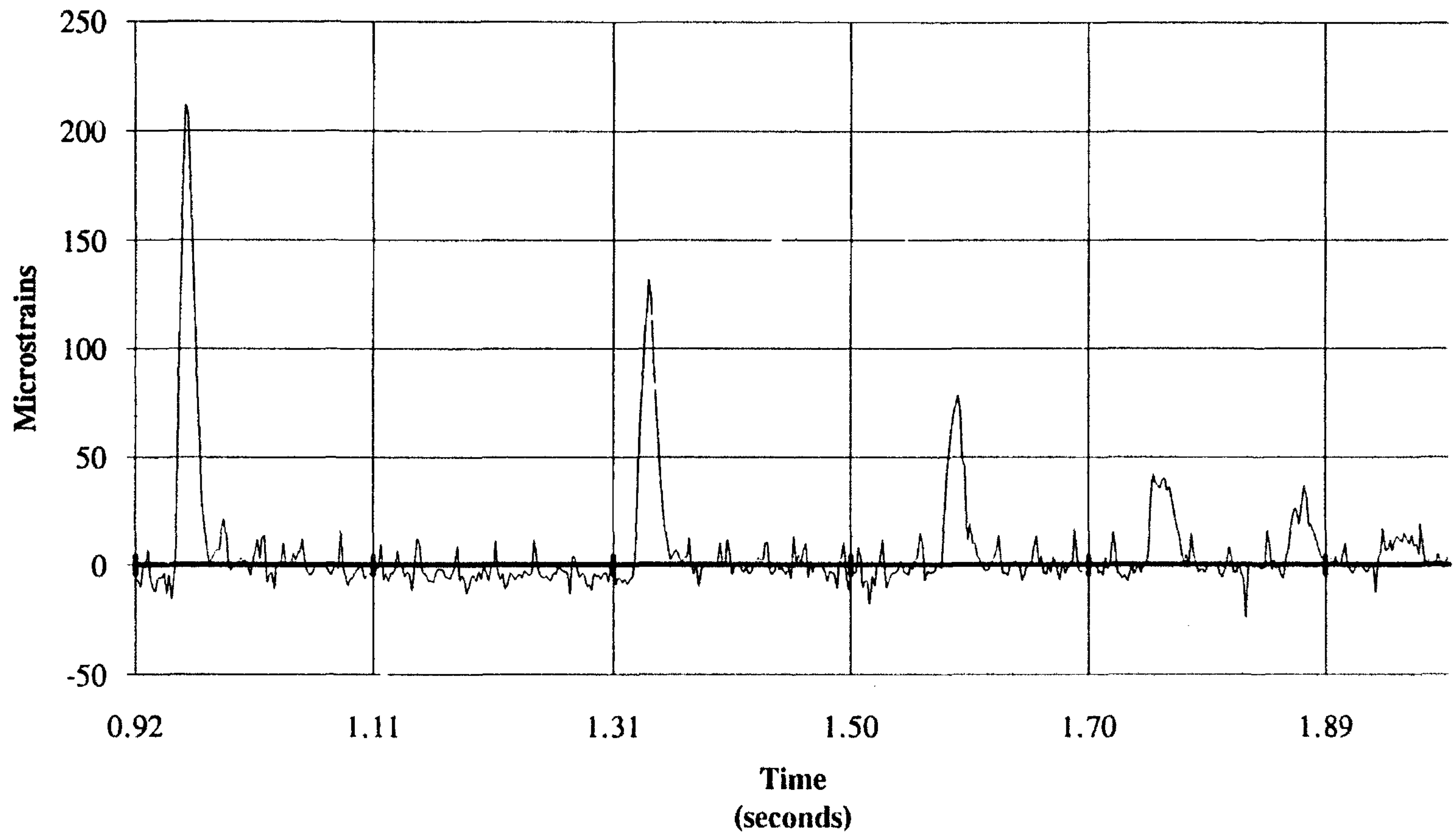

Figure J-1. Strain-Time Plot for Gauge 3BT, Drop Height 2, February 1993 FWD Testing—PACCAR Test Section

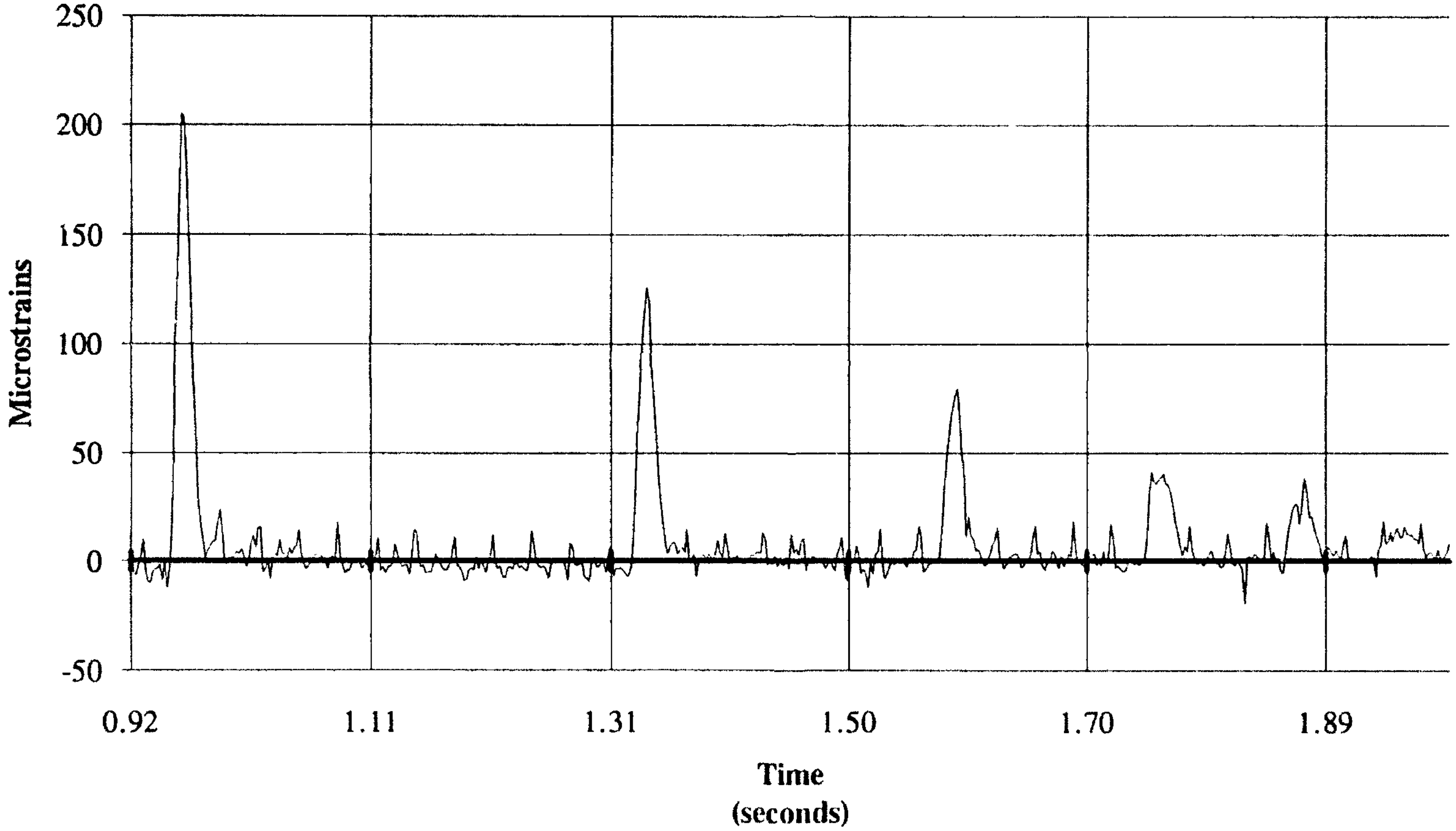

Figure J-2. Strain-Time Plot for Gauge 3BL Drop Height 2, February 1993 FWD Testing—PACCAR Test Section

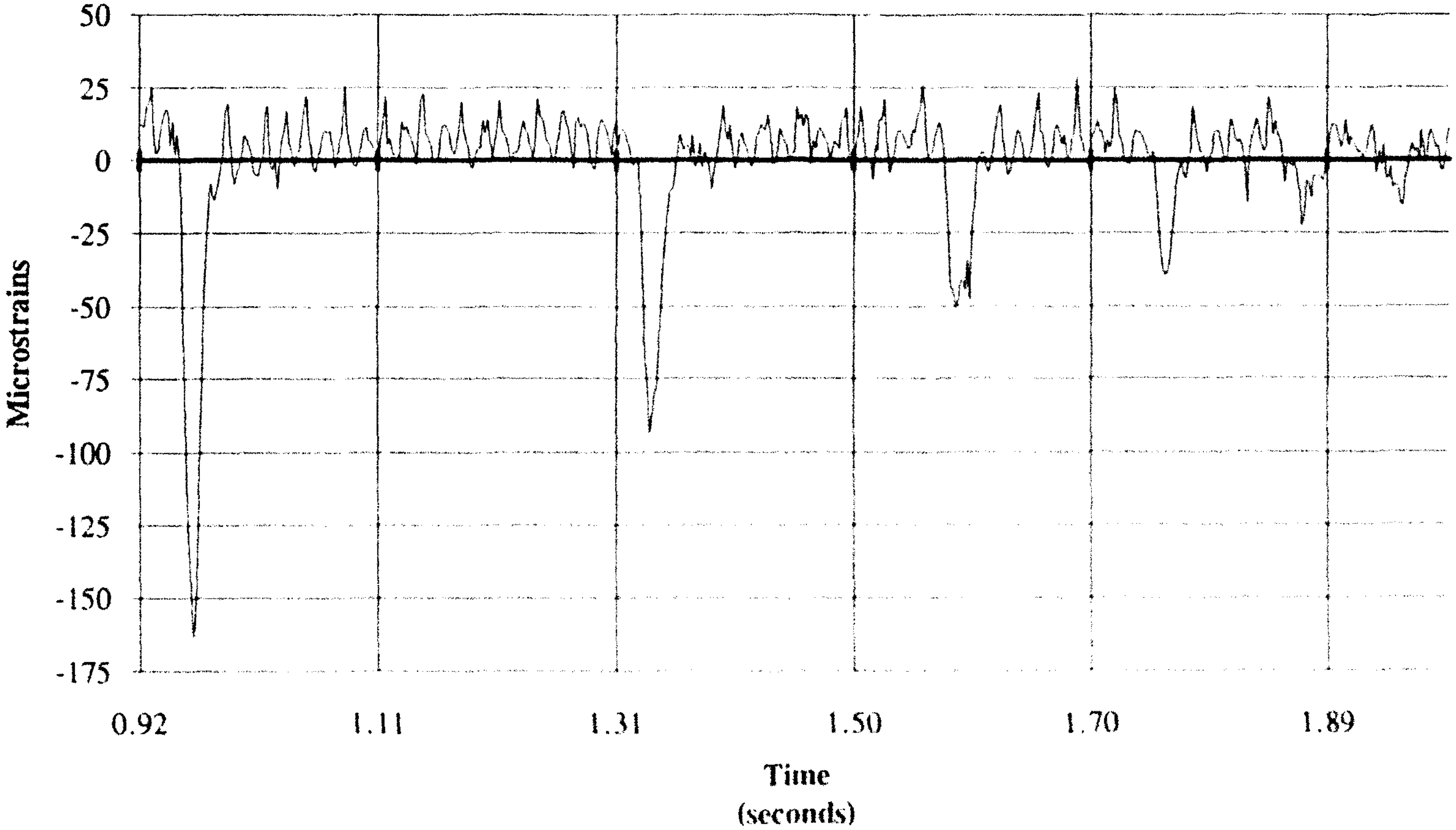

Figure J-3. Strain-Time Plot for Gauge 7SL, Drop Height 2, February 1993 FWD Testing—PACCAR Test Section

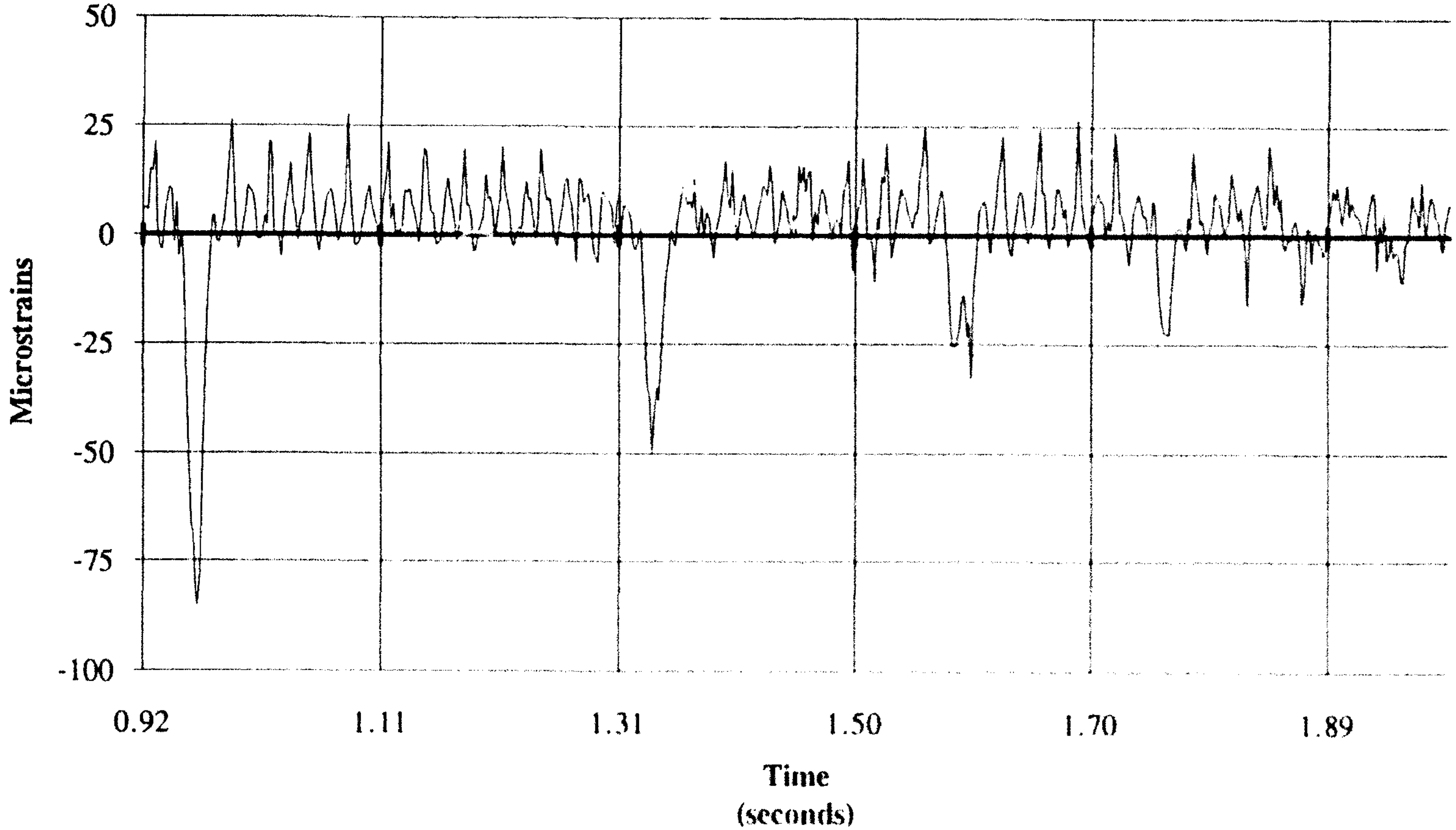

Figure J-4. Strain-Time Plot for Gauge 7ST, Drop Height 2, February 1993 FWD Testing—PACCAR Test Section

APPENDIX K

RD-100 CALIBRATION FOR THE 101-F TEMPERATURE PROBE

Table K-1. RD-100 Calibration for the 101-F Temperature Probe

	Temperature				Temperature		
Reading	Correction	°F	°C	Reading	Correction	°F	°C
-22.7	-17.3	-40.0	-40.0	41.1	-0.1	41.0	5.0
-20.5	-14.1	-34.6	-37.0	42.9	-0.1	42.8	6.0
-18.0	-11.2	-29.2	-34.0	44.7	-0.1	44.6	7.0
-15.1	-8.7	-23.8	-31.0	46.5	-0.1	46.4	8.0
-12.0	-6.4	-18.4	-28.0	48.3	-0.1	48.2	9.0
-8.3	-4.7	-13.0	-25.0	50.0	0.0	50.0	10.0
-4.6	-3.0	-7.6	-22.0	51.7	0.1	51.8	11.0
-0.4	-1.8	-2.2	-19.0	53.4	0.2	53.6	12.0
4.1	-0.9	3.2	-16.0	55.1	0.3	55.4	13.0
5.7	-0.7	5.0	-15.0	56.8	0.4	57.2	14.0
7.3	-0.5	6.8	-14.0	58.4	0.6	59.0	15.0
8.9	-0.3	8.6	-13.0	61.6	1.0	62.6	17.0
10.6	-0.2	10.4	-12.0	66.2	1.8	68.0	20.0
12.2	0.0	12.2	-11.0	70.4	3.0	73.4	23.0
14.0	0.0	14.0	-10.0	74.4	4.4	78.8	26.0
15.7	0.1	15.8	-9.0	78.2	6.0	84.2	29.0
17.5	0.1	17.6	-8.0	81.6	8.0	89.6	32.0
19.3	0.1	19.4	-7.0	84.7	10.3	95.0	35.0
21.1	0.1	21.2	-6.0	87.7	12.7	100.4	38.0
22.9	0.1	23.0	-5.0	90.3	15.5	105.8	41.0
24.7	0.1	24.8	-4.0	92.7	18.5	111.2	44.0
26.5	0.1	26.6	-3.0	94.9	21.7	116.6	47.0
28.3	0.1	28.4	-2.0	96.9	25.1	122.0	50.0
30.2	0.0	30.2	-1.0	98.7	28.7	127.4	53.0
32.0	0.0	32.0	0.0	100.3	32.5	132.8	56.0
33.8	0.0	33.8	1.0	101.8	36.4	138.2	59.0
35.7	-0.1	35.6	2.0	103.6	40.0	143.6	62.0
37.5	-0.1	37.4	3.0	104.3	44.7	149.0	65.0
39.3	-0.1	39.2	4.0				

APPENDIX L

STRAIN GAUGE SPECIFICATIONS—PACCAR TEST SECTION

Table L-1. Strain Gauge Specifications- PACCAR Test Section

Gauge Type	Model Number	Gauge Factor	Transverse Sensitivity Factor
Shear Strain	EA-06-10CBE-120	2.083	n/a
Axial Strain	EA-06-20CBW-120 Lot# R-A38AD591 Batch# S101102	2.055 ± .5	-1.0 ± .2%

Source of Supply: Micro-Measurements, (919) 365-3800